Hashemite University
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Department of earth and environmental sciences

Economic Geology (111201491)
Chapter 2: Igneous Ore-Forming Processes

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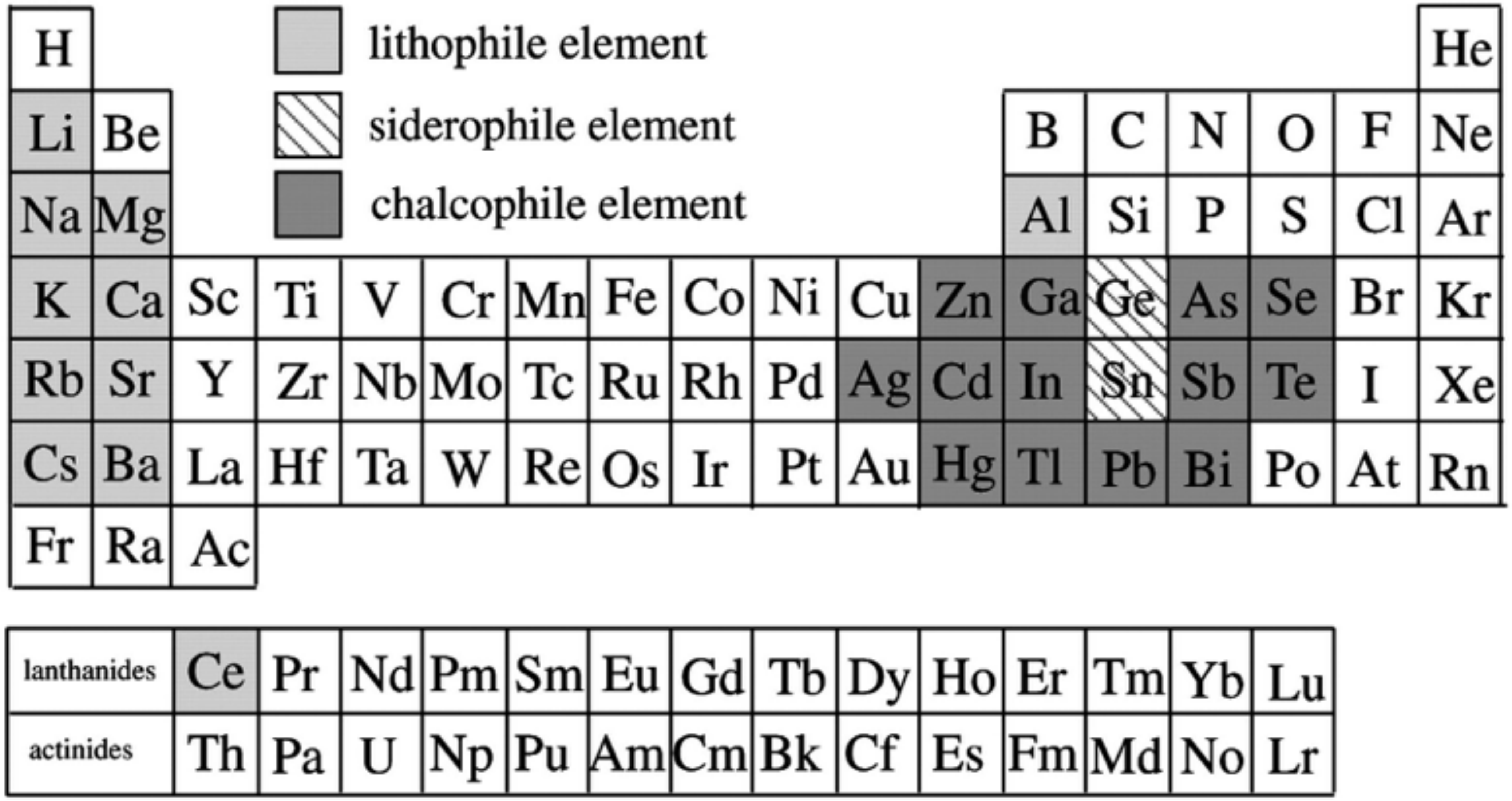
Chapter 2: Igneous Ore-Forming Processes

Igneous rocks host a large number of different ore deposit types. Both mafic and felsic rocks are linked to mineral deposits, examples of which range from the chromite ores resulting from crystal fractionation of mafic magmas to tin deposits associated with certain types of granites.

different igneous rocks host ore deposits with different metal associations, and that this must be related somehow to the **environments in which magmas** are generated and the resulting compositional characteristics they inherit from their various settings.

for example, that many of the chalcophile and siderophile elements (such as Ni, Co, Pt, Pd, and Au) are more likely to be associated with mafic rock types, whereas concentrations of many lithophile elements (such as Li, Sn, Zr, U, and W) are typically found in association with felsic or alkaline rock types.



▨ lithophile element
▧ siderophile element
■ chalcophile element

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

lanthanides	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
actinides	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Crustal architecture and mineral wealth

In fact, most of the world’s economically exploitable mineral wealth effectively lies on the surface or just below the surface of the Earth.

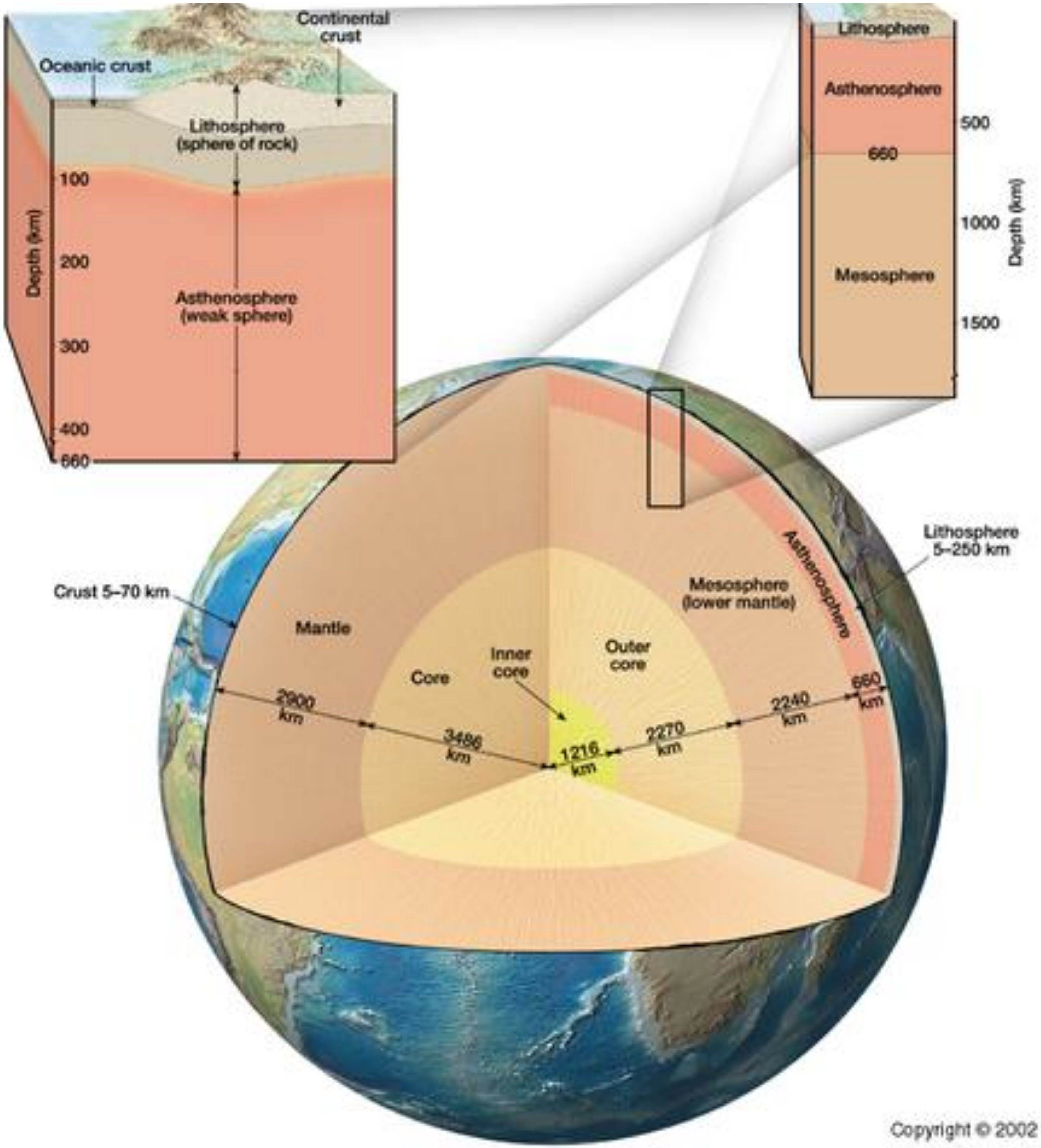
The world’s deepest mine, the Western Deep Levels **gold mine** near Johannesburg, South Africa, extends to just over 4000 m depth

Nevertheless, many mineral commodities are formed much deeper in the crust than 4 km, with some even being derived from the mantle.

Diamonds, for example, are hosted in kimberlite magmas that have been brought to exploitable depths by a variety of igneous or tectonic mechanisms.

A. **The oceanic crust**, which covers some two– thirds of the Earth surface, is thin (less than 10 km) and, compared to the continents, has a composition and structure that is relatively simple and consistent over its entire extent.

The upper layer, on average only 0.4 km thick, comprises a combination of terrigenous and pelagic sediments that are distributed mainly by turbidity currents. They are often highly reduced and metal charged.


Continental crust
Oceanic crust
Lithosphere (sphere of rock)
Asthenosphere (weak sphere)
Depth (km)
100
200
300
400
660
Lithosphere
Asthenosphere
660
Mesosphere
500
1000
1500
Depth (km)
Crust 5–70 km
Mantle
Core
Inner core
Outer core
Mesosphere (lower mantle)
Asthenosphere
Lithosphere 5–250 km
2900 km
3486 km
1216 km
2270 km
2240 km
660 km

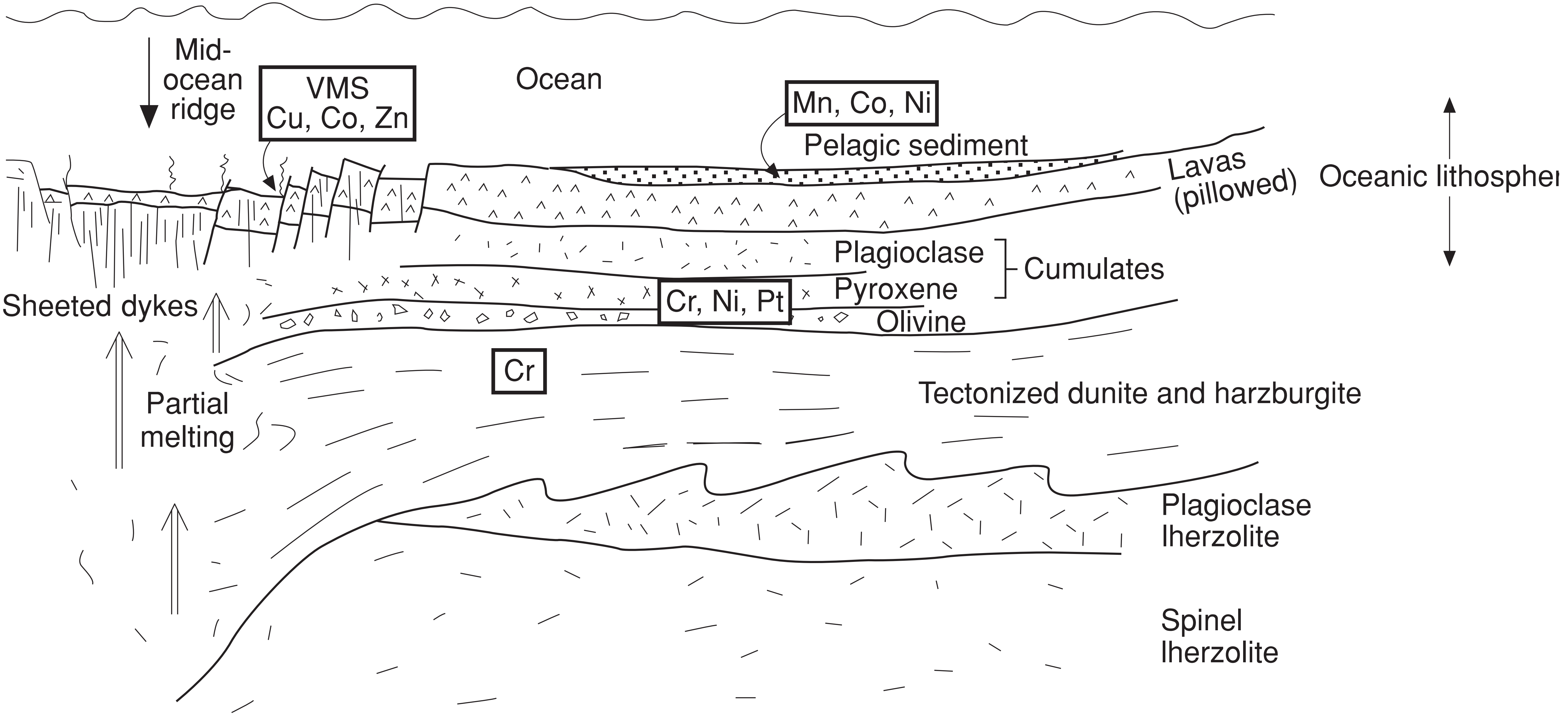


Figure 1.1 Oceanic crustal architecture showing the main types of ore deposits characteristic of this environment. Only chromite and related deposits (Cr–Ni–Pt) are related to igneous ore-forming processes; VMS (Cu, Co, Zn) and sediment-hosted deposits (Mn, Co, Ni) are discussed in Chapters 3 and 5 respectively.

This is underlain by a layer, typically 1–2.5 km thick, that is both extrusive and intrusive in character and dominantly basaltic in composition.

The basalts are, in turn, underlain by the main body of oceanic crust that is plutonic in character and formed by crystallization and fractionation of basaltic magma.

This cumulate assemblage comprises mainly gabbro, pyroxenite, and peridotite.

chromite deposits that are related to crystal fractionation of mid-ocean ridge basalt (MORB), and also have potential for Ni and Pt group element (PGE) mineralization.

Accumulations of manganese in nodules on the sea floor, metal–rich concentrations in pelagic muds, and volcanogenic massive sulfide (VMS) Cu-Zn deposits also occur in this tectonic setting, but are not directly related to igneous processes.

B. The continental crust differs markedly from its oceanic counterpart.

It is typically 35 – 40 km thick, but thins to around 20 km under rift zones and thickens to 80 km or more beneath young mountain belts.

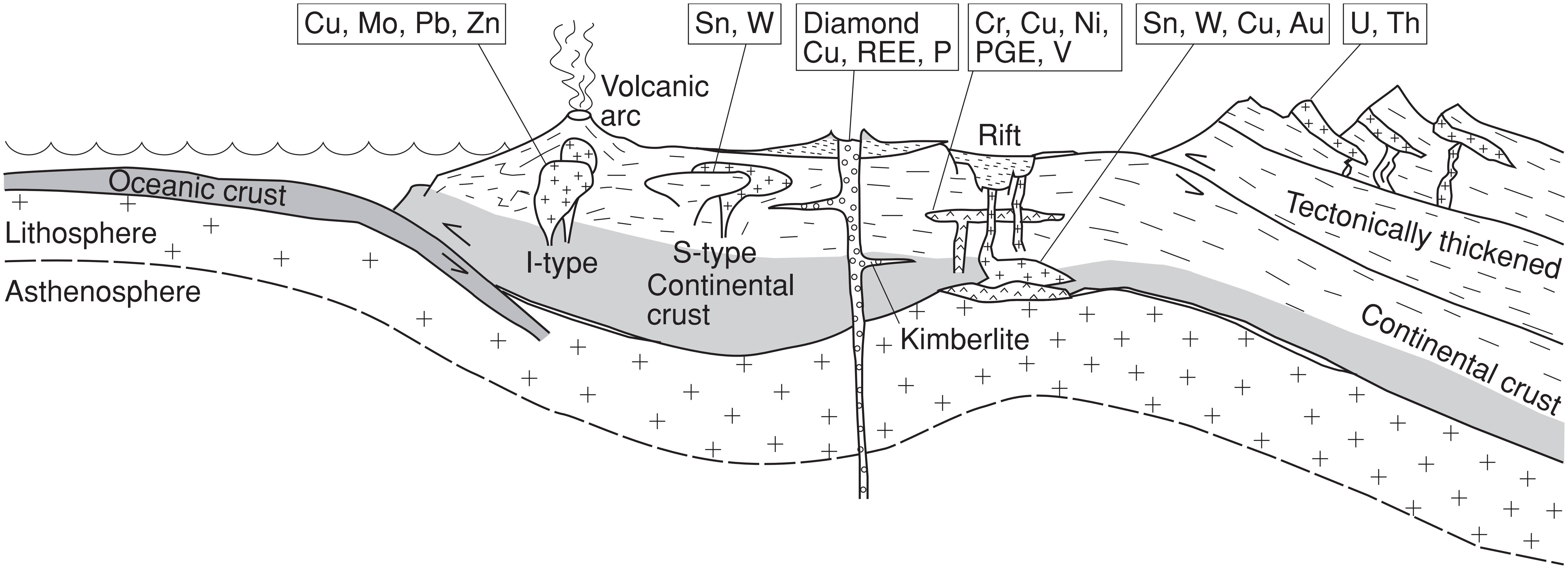


Figure 1.2 Continental crustal architecture showing the main types of igneous-related ore deposits characteristic of this environment.

Historically, the continental crust was thought to comprise an upper zone made up largely of granite (and its sedimentary derivatives) and a lower, more mafic zone, with the two layers separated by the Conrad discontinuity (which marks a change in seismic velocities, and, therefore crustal density).

The upper crust, which in some continental sections is defined as extending to the Conrad discontinuity at some 6 km depth, is made up of felsic to intermediate compositions (granite to diorite) together with the sedimentary detritus derived from the weathering and erosion of this material.

Most of the world’s known ore deposits are, of course, hosted in rocks of the continental crust.

deposit types are shown and these include diamondiferous kimberlites, anorthosite–hosted Ti deposits, the Cr-V-Pt-Cu-Ni assemblage of ores in continental layered mafic suites, and the Sn-W-F-Nb-REE-P-U family of lithophile ores related to granites and alkaline intrusions.

Magma types and metal contents

the outer two layers of the Earth, the more rigid lithosphere and the ductile asthenosphere, are largely solid.

Zones within these layers that are anomalous in terms of pressure or temperature do, however, form and can cause localized melting of the rocks present.

The nature of the rock undergoing melting and the extent to which it is melted are the main factors that control the composition of the magma that is formed.

The magma composition, in turn, dictates the nature of metal concentrations that are likely to form in the rocks that solidify from that magma.

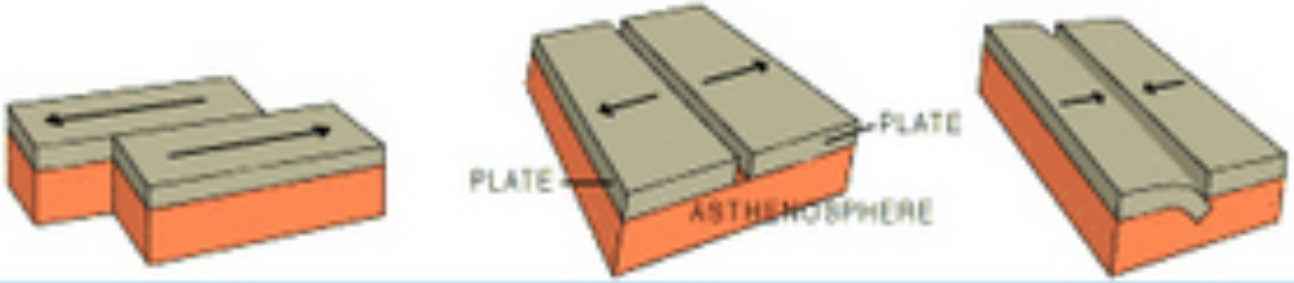
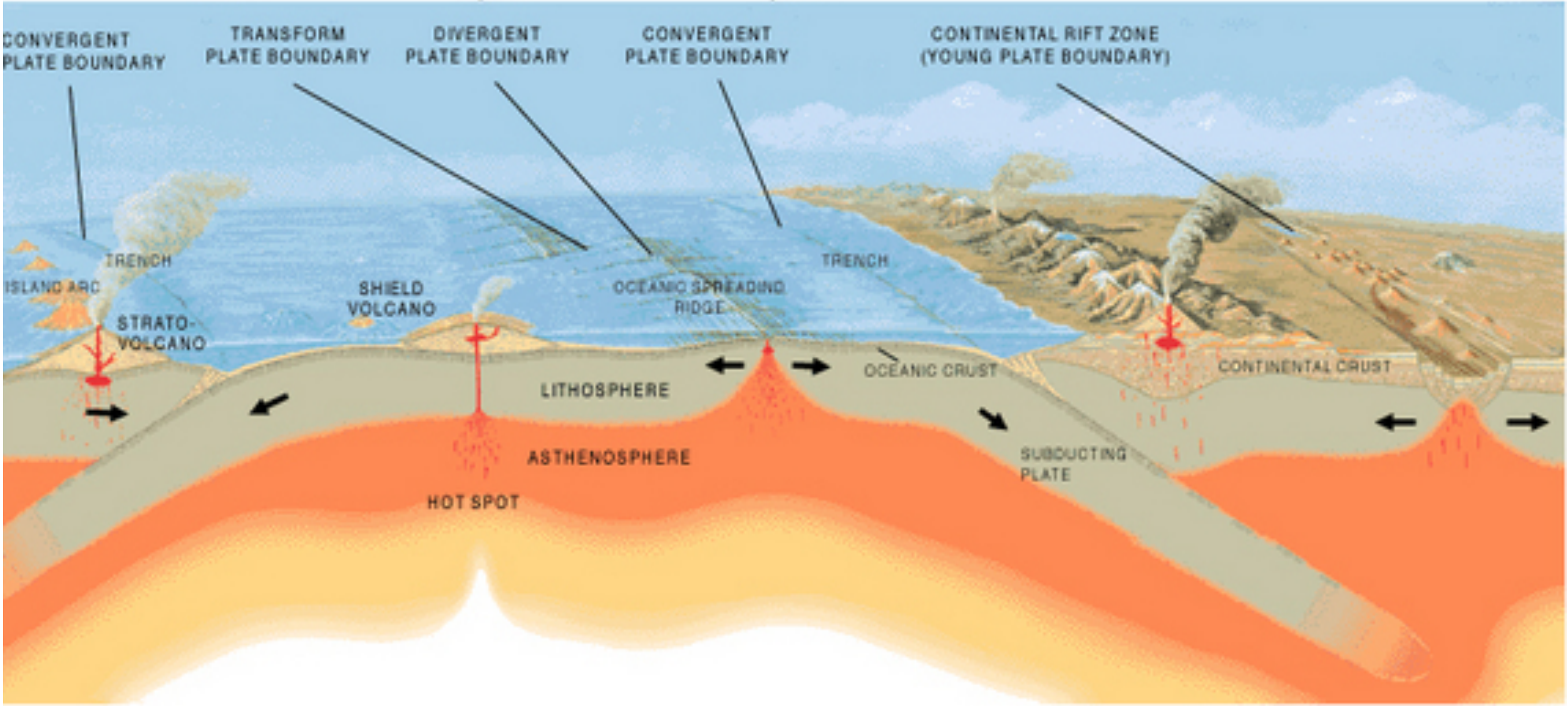
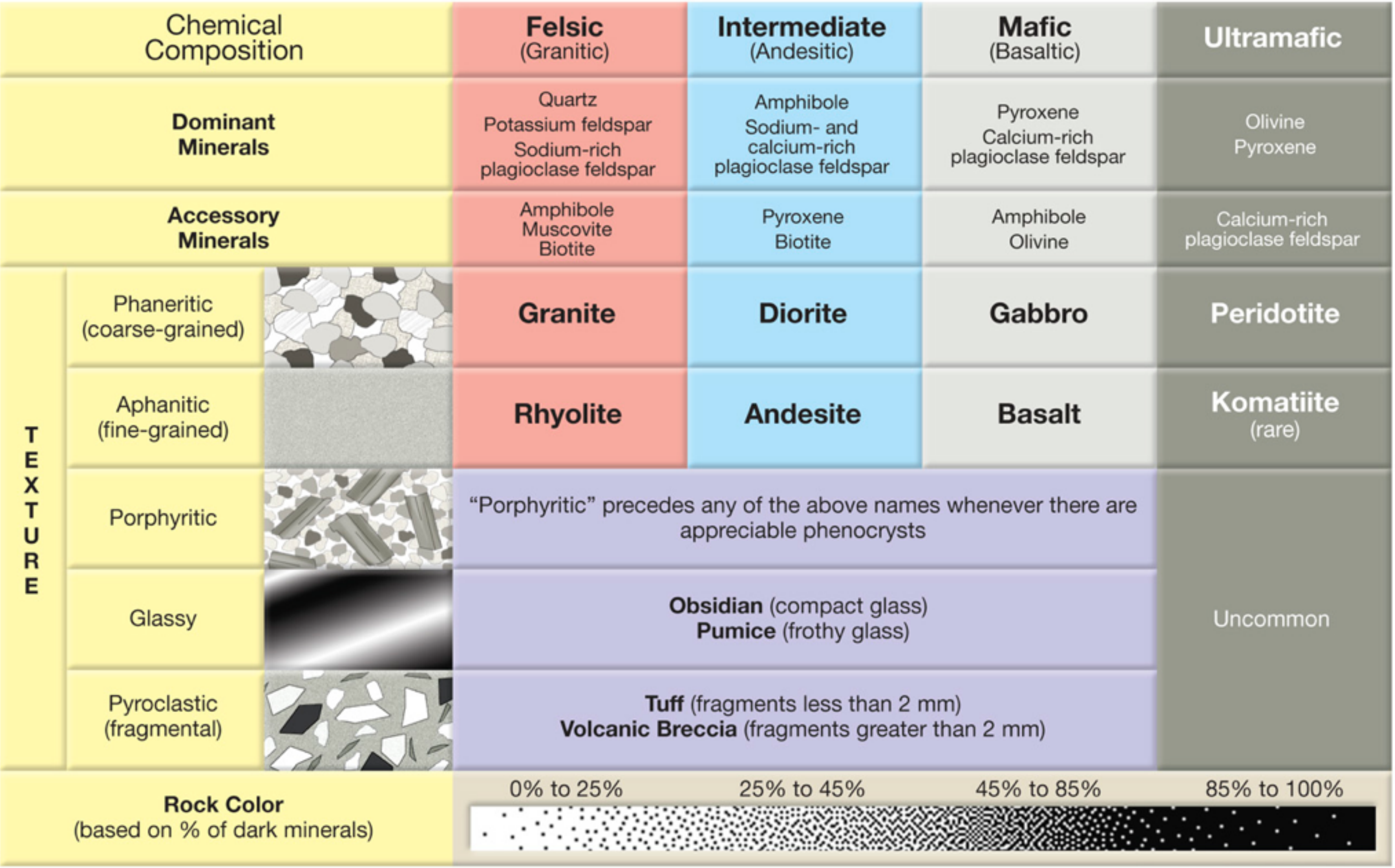


PLATE
PLATE
ASTHENOSPHERE


CONVERGENT PLATE BOUNDARY
TRANSFORM PLATE BOUNDARY
DIVERGENT PLATE BOUNDARY
CONVERGENT PLATE BOUNDARY
CONTINENTAL RIFT ZONE (YOUNG PLATE BOUNDARY)
TRENCH
ISLAND ARC
STRATO-VOLCANO
SHIELD VOLCANO
OCEANIC SPREADING RIDGE
TRENCH
OCEANIC CRUST
CONTINENTAL CRUST
LITHOSPHERE
ASTHENOSPHERE
HOT SPOT
SUBDUCTING PLATE

A Fundamental Magma Type – These Are

1. Basalt,
2. Andesite,
3. Rhyolite, And
4. Alkaline Magmas Including Kimberlite.



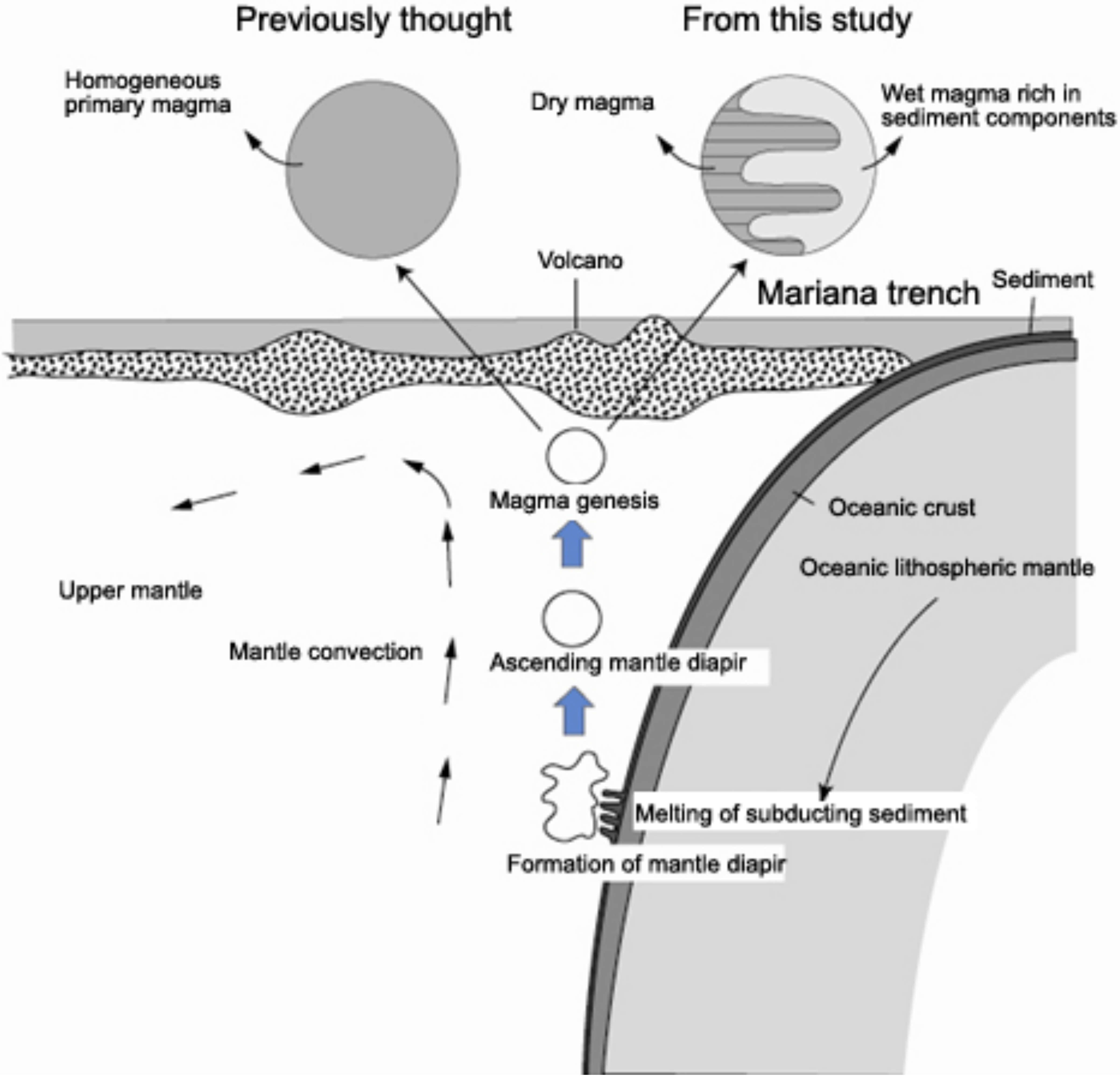
Chemical Composition		Felsic (Granitic)	Intermediate (Andesitic)	Mafic (Basaltic)	Ultramafic
Dominant Minerals		Quartz Potassium feldspar Sodium-rich plagioclase feldspar	Amphibole Sodium- and calcium-rich plagioclase feldspar	Pyroxene Calcium-rich plagioclase feldspar	Olivine Pyroxene
Accessory Minerals		Amphibole Muscovite Biotite	Pyroxene Biotite	Amphibole Olivine	Calcium-rich plagioclase feldspar
TEXTURE	Phaneritic (coarse-grained)	**Granite**	**Diorite**	**Gabbro**	**Peridotite**
	Aphanitic (fine-grained)	**Rhyolite**	**Andesite**	**Basalt**	**Komatiite** (rare)
	Porphyritic	"Porphyritic" precedes any of the above names whenever there are appreciable phenocrysts			Uncommon
	Glassy	**Obsidian** (compact glass) **Pumice** (frothy glass)			
	Pyroclastic (fragmental)	**Tuff** (fragments less than 2 mm) **Volcanic Breccia** (fragments greater than 2 mm)			
Rock Color (based on % of dark minerals)		0% to 25%	25% to 45%	45% to 85%	85% to 100%

1. Basaltic magma

Basalt forms by partial melting of mantle material, much of which can generally be described as peridotitic in composition.

The major elements that characterize a basaltic magma (Mg and Fe) and dictate its mineral composition (olivine and the pyroxenes)

The majority of basaltic magma production takes place along the:

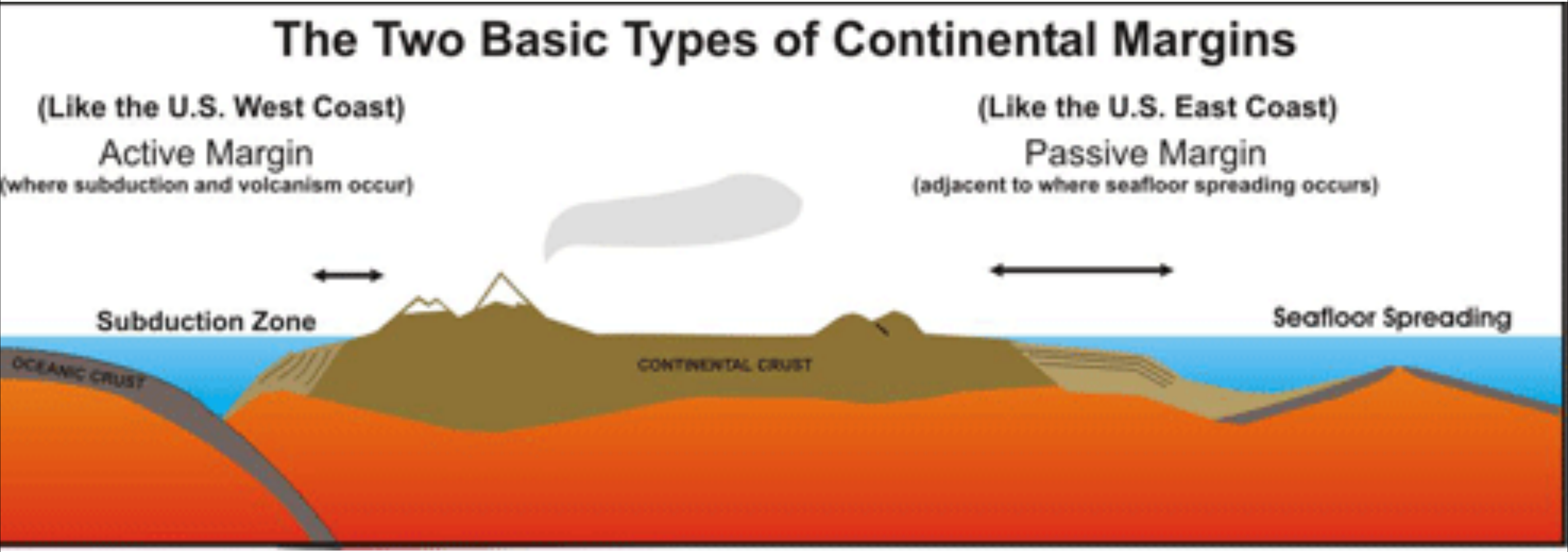


1. **Mid-ocean ridges**, and in response to hot-spot related plumes, to form oceanic crust.
2. Along island arcs and
3. Orogenic continental margins.

Basaltic magma may also <u>intrude</u> or <u>extrude</u> continental crust, either along well defined

1. Fractures Or
2. Rifts Or

in response to intra- plate hot-spot activity


The Two Basic Types of Continental Margins
(Like the U.S. West Coast)
Active Margin
(where subduction and volcanism occur)
(Like the U.S. East Coast)
Passive Margin
(adjacent to where seafloor spreading occurs)
Subduction Zone
Seafloor Spreading
OCEANIC CRUST
CONTINENTAL CRUST

Ore deposits associated with mafic igneous rocks typically Ni, Co, Cr, V, Cu, Pt, and Au.

The enhanced concentration of these metals in each case is related to the fact that the source materials from which the basalt formed.

Table 1.2 Average abundances of selected elements in the major magma types

	Basalt	Andesite	Rhyolite	Alkaline magma	Kimberlite	Clarke[*]
Li	10	12	50	–	–	20
Be	0.7	1.5	4.1	4–24	–	2.8
F	380	210	480	640	–	625
P	3200	2800	1200	1800	0.6–0.9%	1050
V	266	148	72	235	–	135
Cr	307	55	4	–	–	10
Co	48	24	4.4	–	–	25
Ni	134	18	6	–	1050	75
Cu	65	60	6	–	103	55
Zn	94	87	38	108	–	70
Zr	87	205	136	1800	2200	165
Mo	0.9–2.7	0.8–1.2	1	15	–	1.5
Sn	0.9	1.5	3.6	–	–	2
Nb	5	4–11	28	140	240	20
Sb	0.1–1.4	0.2	0.1–0.6	–	–	0.2
Ta	0.9	–	2.3	10	–	2
W	1.2	1.1	2.4	16	–	1.5
Pb	6.4	5	21	15	–	13
Bi	0.02	0.12	0.12	–	–	0.17
U	0.1–0.6	0.8	5	10	–	2.7
Th	0.2	1.9	26	35	–	7.2
Ag[†]	100	80	37	–	–	70
Au[†]	3.6	–	1.5	–	–	4
Pt[†]	17–30	–	3–12	–	19	10
S	782	423	284	598	2100	260
Ge	1.1	1.2	1.0–1.3	1.3–2.1	0.5	1.5
As	0.8	1.8	3.5	–	–	1.8
Cd	0.02	0.02	0.2–0.5	0.04	–	0.2

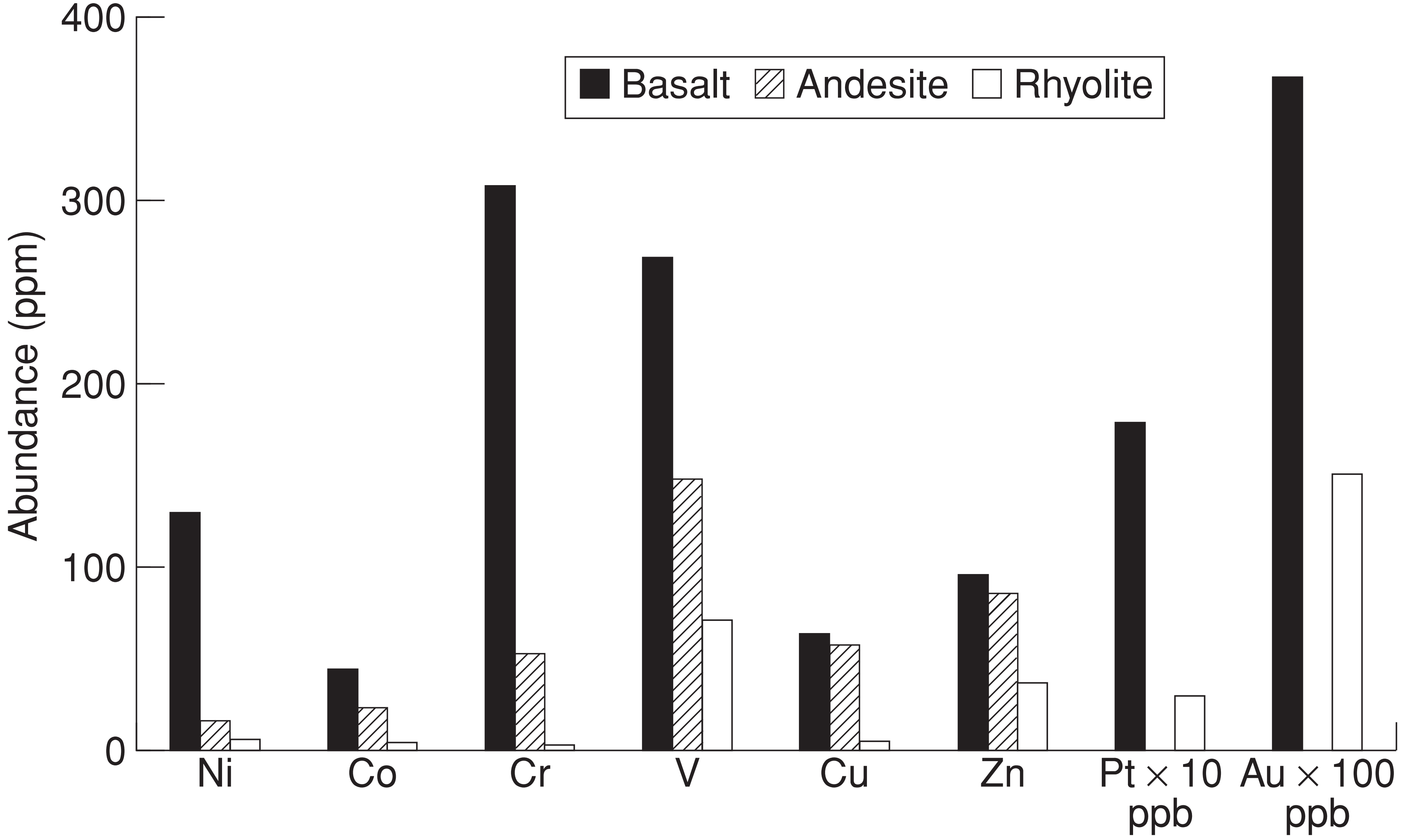


Figure 1.3 Relative abundances of selected metals in basalt, andesite, and rhyolite (data from Table 1.2).

2. Andesitic

Andesites are rocks that crystallize from magmas of composition intermediate between basalt and rhyolite (typically with SiO_2 contents between 53 and 63 wt%).

occur dominantly:

1. in orogenic zones,
2. along island arcs or
3. on continental margins beneath which subduction of oceanic crust

Andesite can be formed:

a. as a primary magma composition derived directly by an appropriate degree of melting of a suitable source rock

or

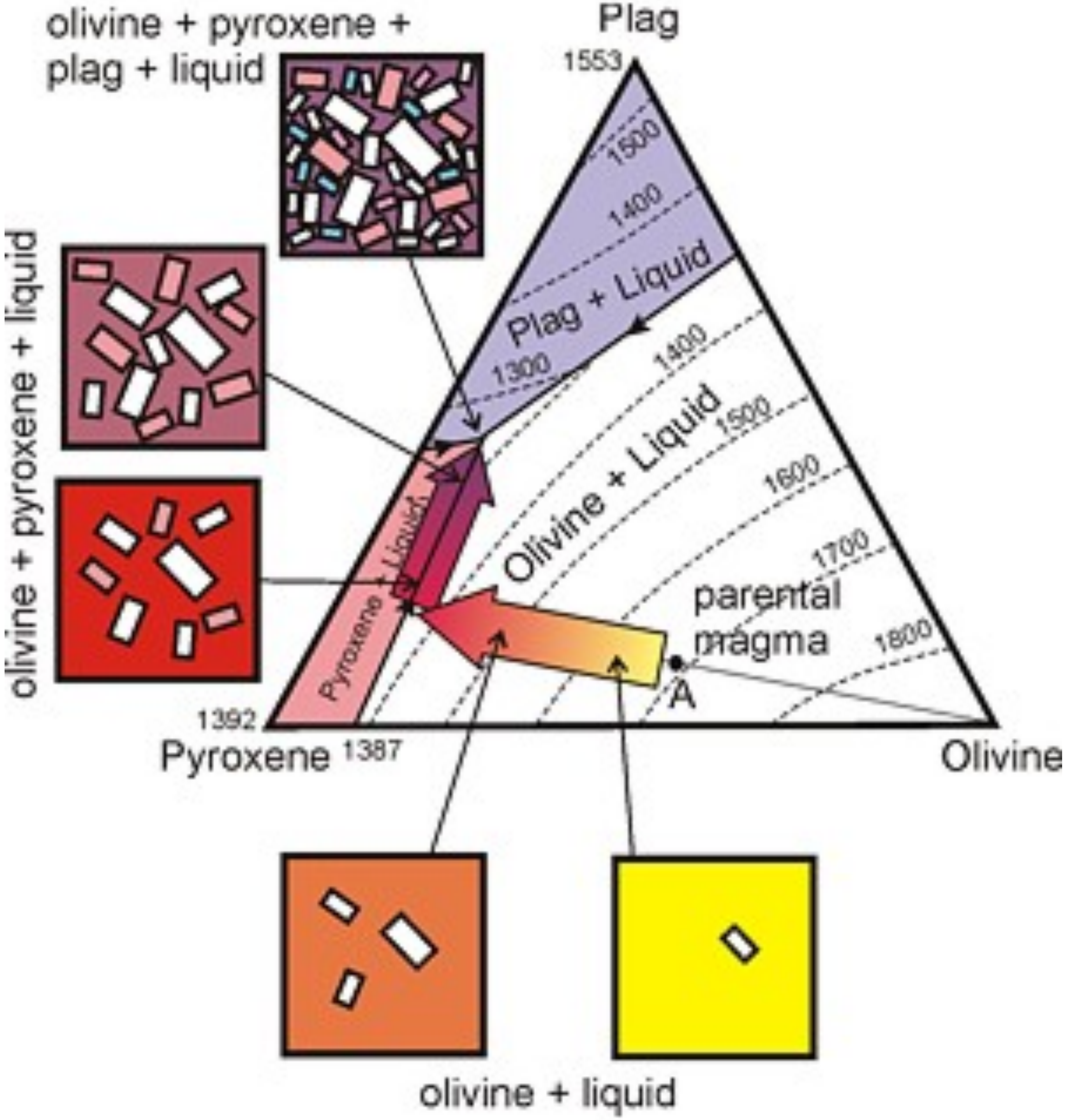
an evolved melt formed by differentiation of a more mafic magma such as basalt.

b. by in situ fractionation of phases such as hornblende and magnetite from relatively water–rich parent magmas, or

c. by contamination of an originally more mafic melt by felsic material or melt.

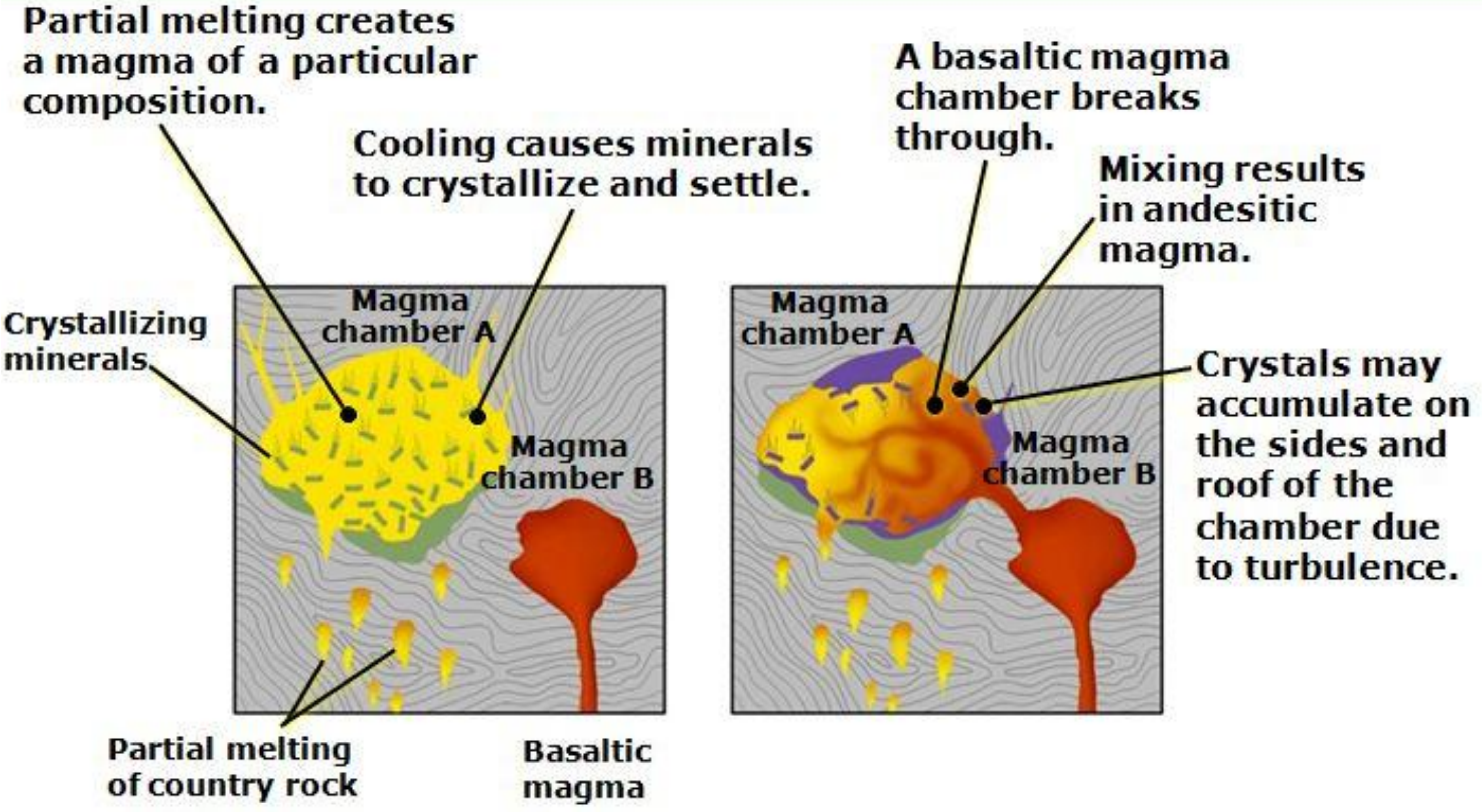
Intermediate melt compositions are simply characterized by intermediate trace element abundances.

Andesites appear to have little or no metal specificity and are characterized by trace element abundances that are intermediate between those of basalt on the one hand and either granite or alkaline rocks on the other.



fractionation

Magmatic Differentiation: The Mush (magma) chamber



Partial melting creates a magma of a particular composition.

Cooling causes minerals to crystallize and settle.

A basaltic magma chamber breaks through.

Mixing results in andesitic magma.

Crystals may accumulate on the sides and roof of the chamber due to turbulence.

3. Rhyolite

Felsic magmas crystallize at depth to form a spectrum of rock compositions ranging from Na–rich tonalite to K–rich alkali granite,

or

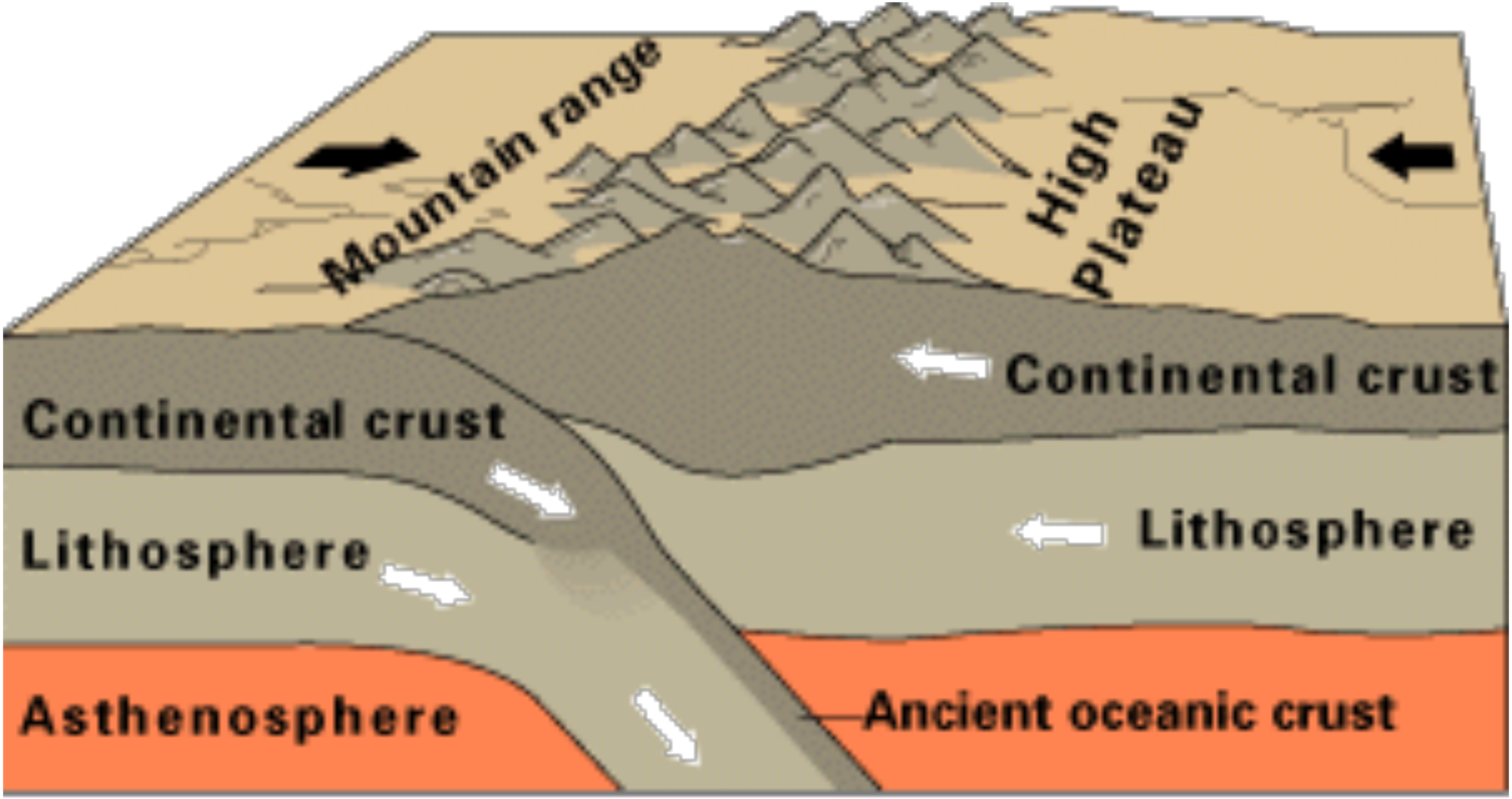
extrude on surface to form dacitic to rhyolitic volcanic rocks.

Granitic melts can be the products of differentiation of more mafic magmas in oceanic settings.

Most felsic magmas, however, are derived from the partial melting of predominantly crustal material along ocean-continent island arcs and orogenic continental margins.

Significant quantities of felsic magma are produced in the latter stages of continent-continent collision and also in anorogenic continental settings where rifting and crustal thinning has taken place. Himalayan–type continent collision

Ore deposits associated with felsic igneous rocks often comprise concentrations of the lithophile elements such as Li, Be, F, Sn, W, U, and Th.



Continental-continental convergence

4. Alkaline magmas and kimberlite

magmas that are depleted in SiO_2 but highly enriched in the alkali elements (Na, K, and Ca) are

Economically important as they frequently contain impressive concentrations of a wide range of ore–forming metals (such as Cu, Fe, P, Zr, Nb, REE, F, U, and Th).

The most common alkaline mafic magma is nephelinite, which crystallizes to give a range of rock types comprising rather unusual minerals, such as felspathoid, calcic–pyroxene, and carbonate assemblages.

Nephelinite associated carbonatite melts (i.e. magmas comprising essentially $CaCO_3$ and lesser Na_2CO_3

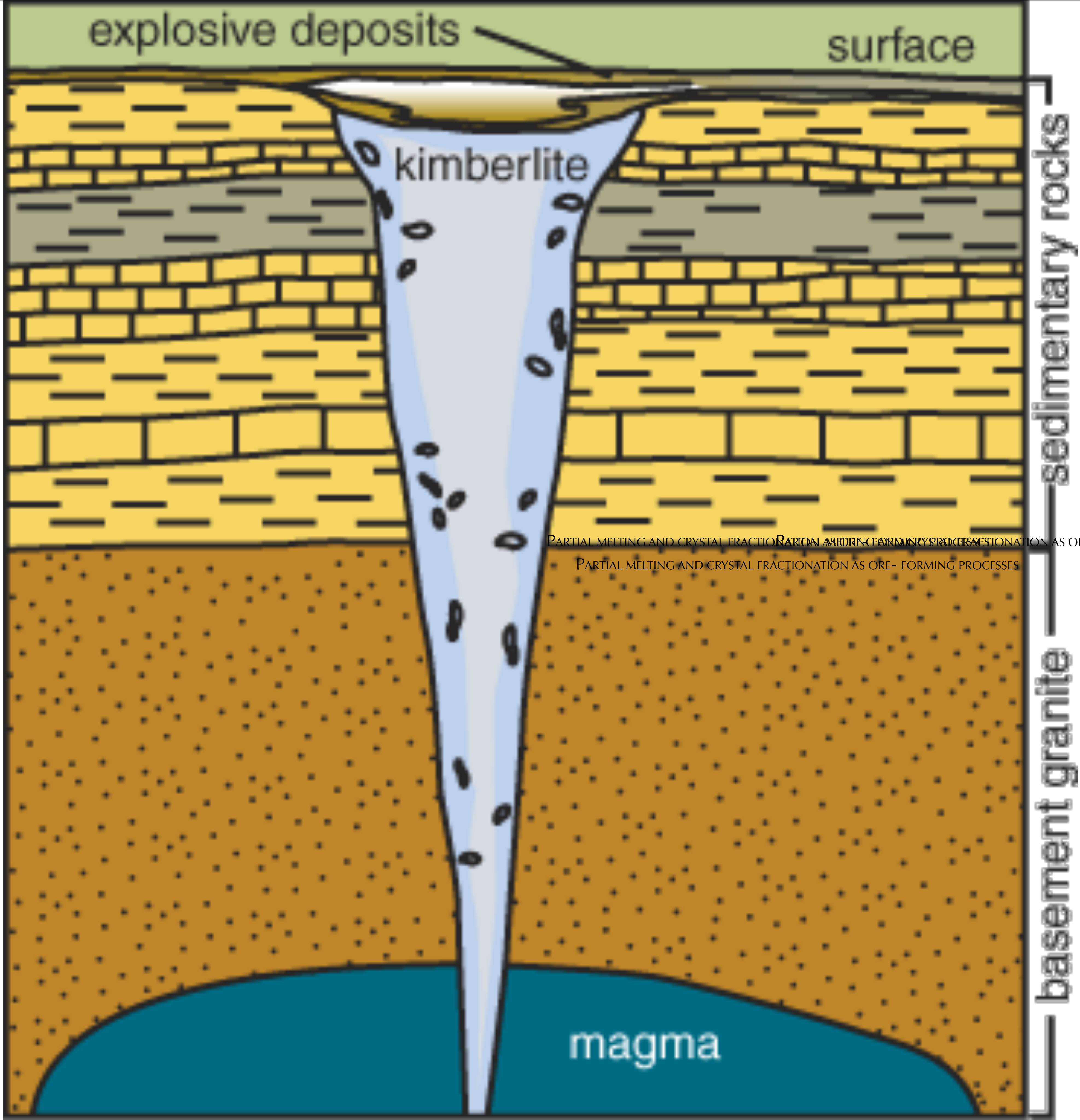
Kimberlitic and related ultramafic magmas crystallize to form very rare and unusual rocks, containing among other minerals both mica and olivine.

Kimberlites are rich in potassium (K_2O typically 1–3 wt %) and, although derived from deep in the mantle, are also hydrated and carbonated.

They usually occur in small (<1 km diameter) pipe-like bodies, or dykes and sills, and commonly extrude in highly explosive, gas-charged eruptions.

kimberlitic and related magma types are the main primary source of diamonds.

Diamond is the stable carbon polymorph under very reducing conditions, and at depths in excess of about 100 km and temperatures greater than 900 °C



Partial melting and crystal fractionation as ore- forming processes

Partial melting and crystal fractionation as ore- forming processes

Variation of magma compositions

Magmatic Differentiation: Any process that causes magma composition to change

Among the processes are:

1. Distinct melting events from distinct sources.
2. Various degrees of partial melting from the same source.
3. Crystal fractionation.
4. Mixing of 2 or more magmas.
5. Assimilation/contamination of magmas by crustal rocks.
6. Liquid Immiscibility.

1. Distinct Melting Events

Magmas are not related except by some heating event that caused melting. In such a case each magma might represent melting of a different source rock at different times during the heating event. If this were the case, we might not expect the chemical analyses of the rocks produced to show smooth trends on variation diagrams. But, because variation diagrams are based on a closed set of numbers (chemical analyses add up to 100%), if the weight% of one component increases, then the weight percent of some other component must decrease. Thus, even in the event that the magmas are not related, SiO_2 could increase and MgO could decrease to produce a trend. The possibility of distinct melting events is not easy to prove or disprove.

2. Various Degrees of Partial Melting

When a multicomponent rock system melts, it melts over a range of temperatures at any given pressure, and during this melting, the liquid composition changes.

Thus, a wide variety of liquid compositions could be made by various degrees of partial melting of the same source rock

Trace Elements as Clues to Suites Produced by Various Degrees of Melting

Trace elements are elements that occur in low concentrations in rocks, usually less than 0.1 % (usually reported in units of parts per million, ppm).

When considering the rocks in the mantle, trace elements can be divided into

incompatible elements, those that do not easily fit into the crystal structure of minerals in the mantle, and

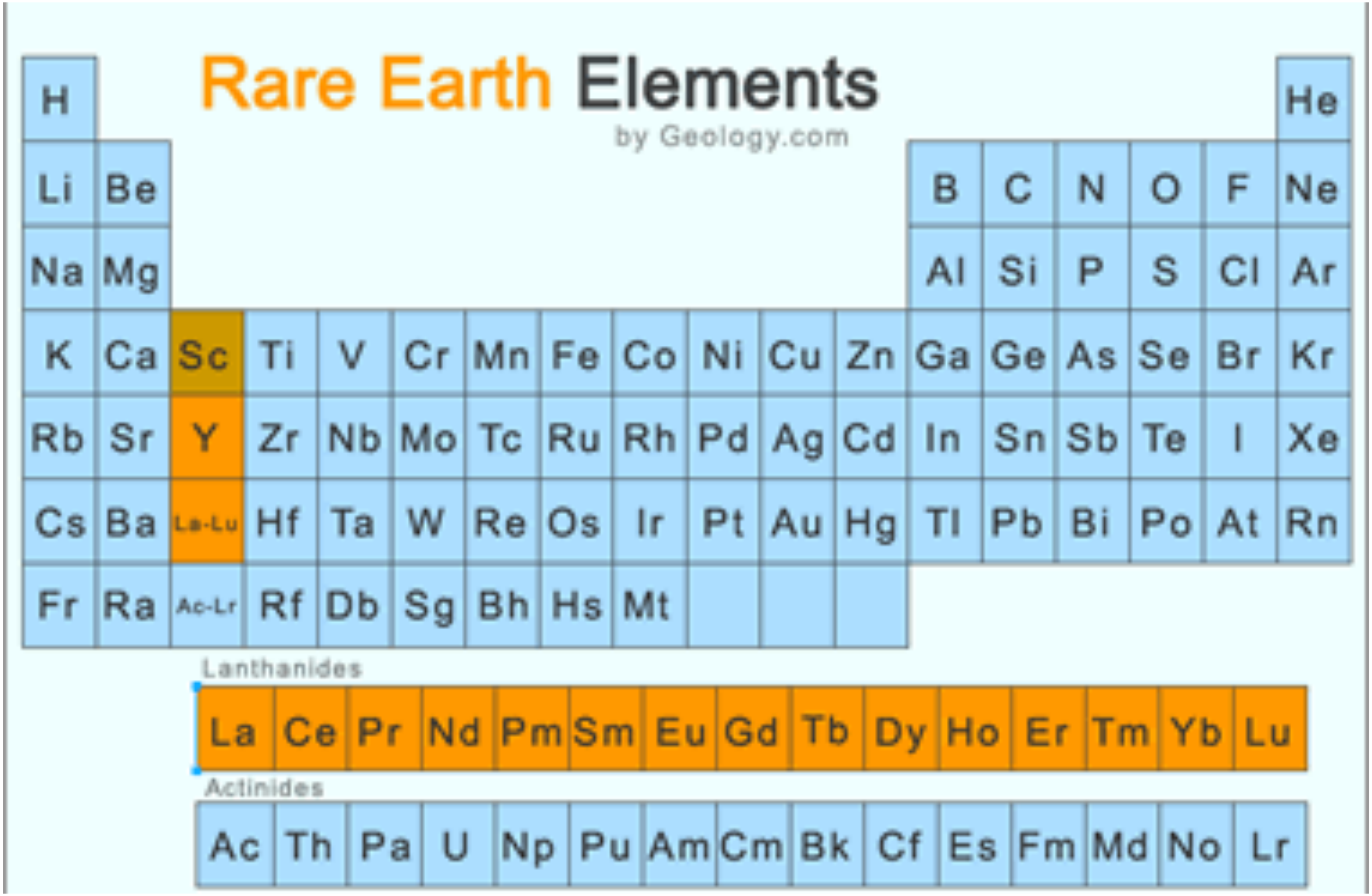
compatible elements, those that do fit easily into the crystal structure of minerals in the mantle.

Incompatible elements – these are elements like K, Rb, Cs, Ta, Nb, U, Th, Y, Hf, Zr, and the Rare Earth Elements (REE)– La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, & Lu.

Most have a large ionic radius.

Mantle minerals like olivine, pyroxene, spinel, & garnet do not have crystallographic sites for large ions.

Compatible elements – these are elements like Ni, Cr, Co, V, and Sc, which have smaller ionic radii and fit more easily into crystallographic sites that normally accommodate Mg, and Fe.



Rare Earth Elements

by Geology.com

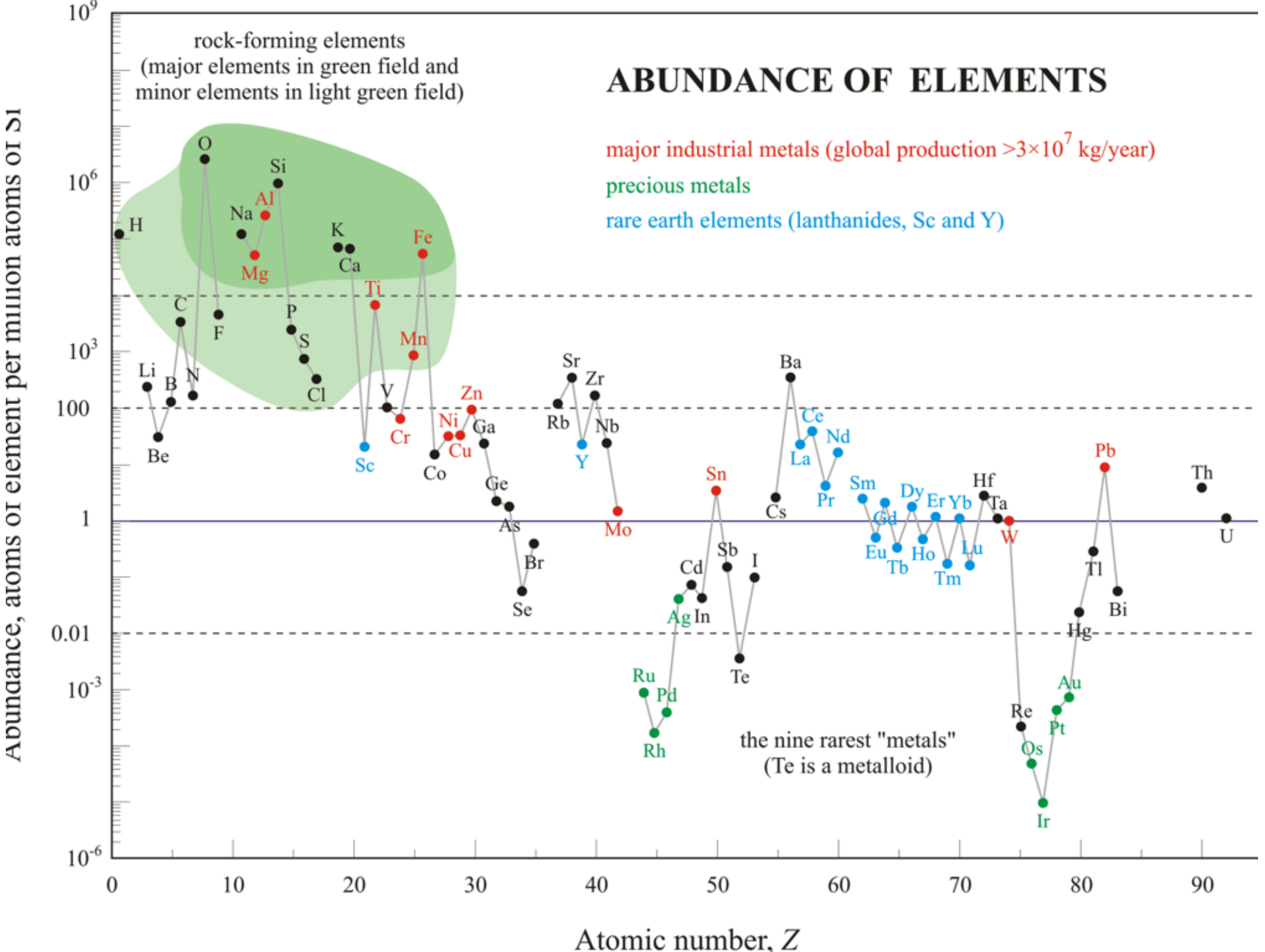
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt									

Lanthanides

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

Actinides

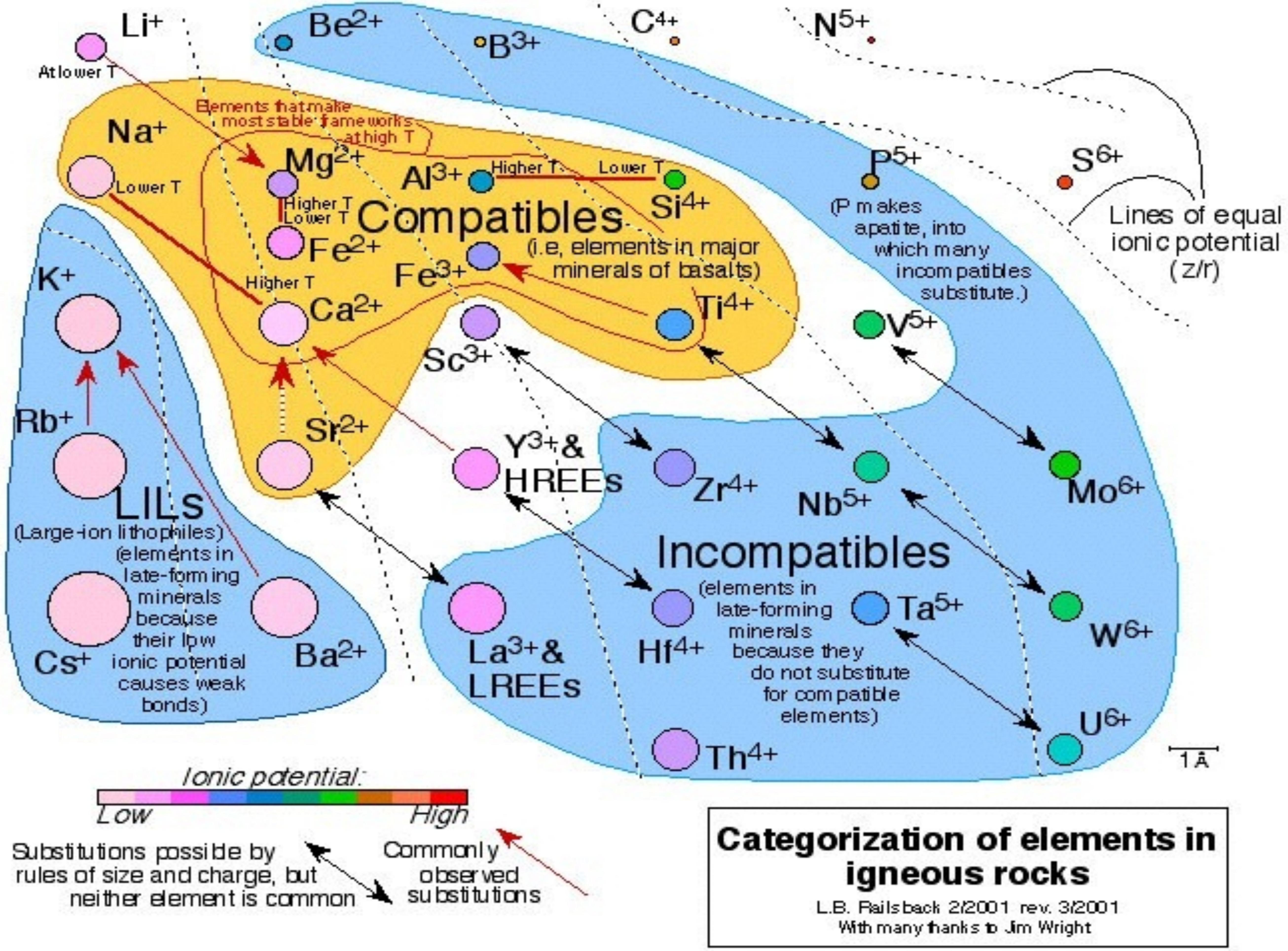
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr


ABUNDANCE OF ELEMENTS
rock-forming elements
(major elements in green field and
minor elements in light green field)
major industrial metals (global production >3×10^7 kg/year)
precious metals
rare earth elements (lanthanides, Sc and Y)
the nine rarest "metals"
(Te is a metalloid)
Abundance, atoms of element per million atoms of Si
Atomic number, Z
10^9
10^6
10^3
100
1
0.01
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
H
Li
Be
B
C
N
O
F
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

When a mantle rock begins to melt, the incompatible elements will be ejected preferentially from the solid and enter the liquid.

Thus, a low degree melt of a mantle rock will have high concentrations of incompatible elements.

As melting proceeds the concentration of these incompatible elements will decrease because (1) there will be less of them to enter the melt, and (2) their concentrations will become more and more diluted as other elements enter the melt. Thus, **incompatible element concentrations will decrease with increasing % melting**.



Categorization of elements in igneous rocks

L.B. Railsback 2/2001 rev. 3/2001

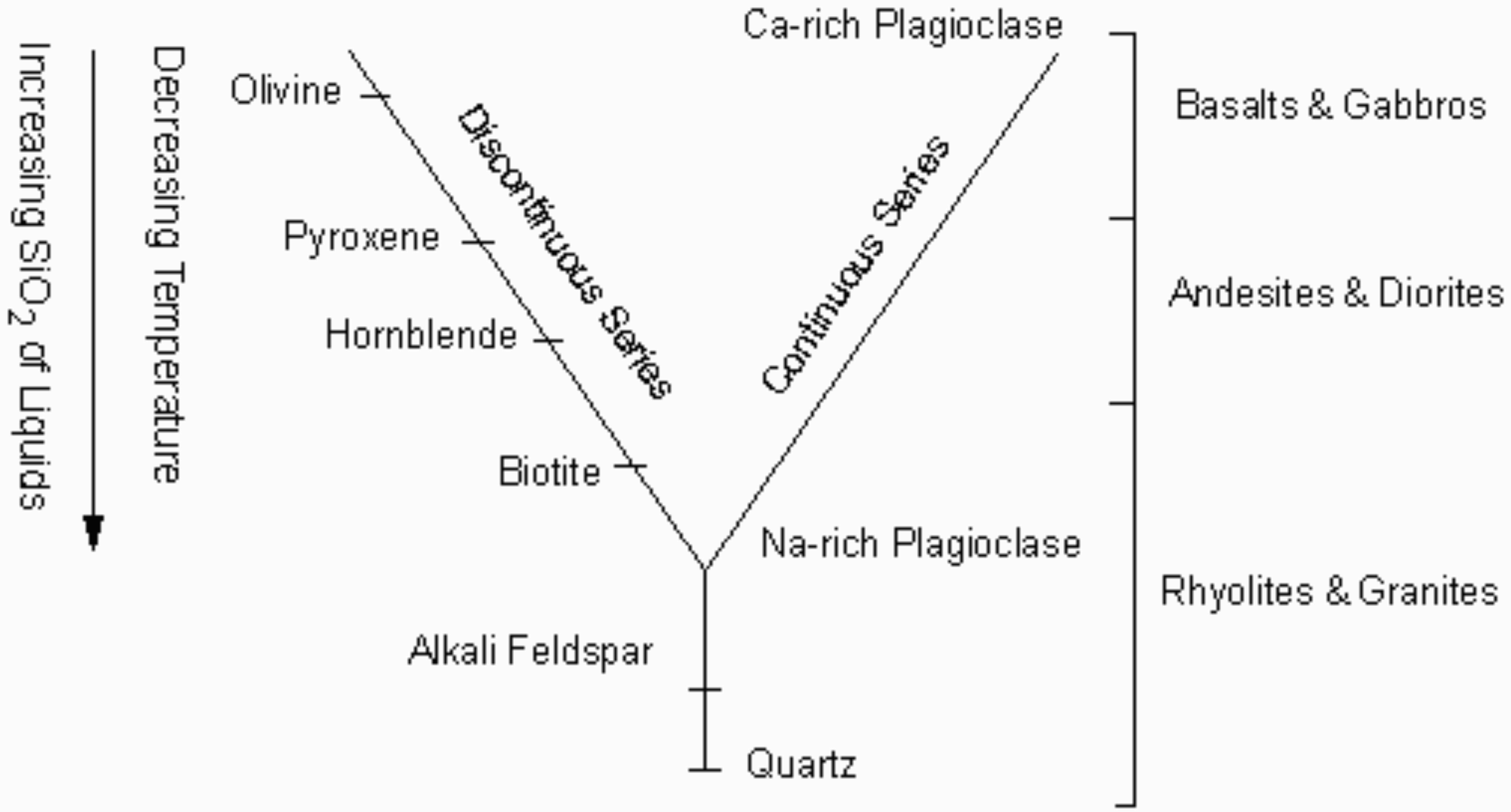
With many thanks to Jim Wright

3. Crystal Fractionation

crystallization results in a change in the composition of the liquid, and if the crystals are removed by some process, then different magma compositions can be generated from the initial parent liquid.

If minerals that later react to form a new mineral or solid solution minerals are removed, then crystal fractionation can produce liquid compositions that would not otherwise have been attained by normal crystallization of the parent liquid.

Bowen's Reaction Series

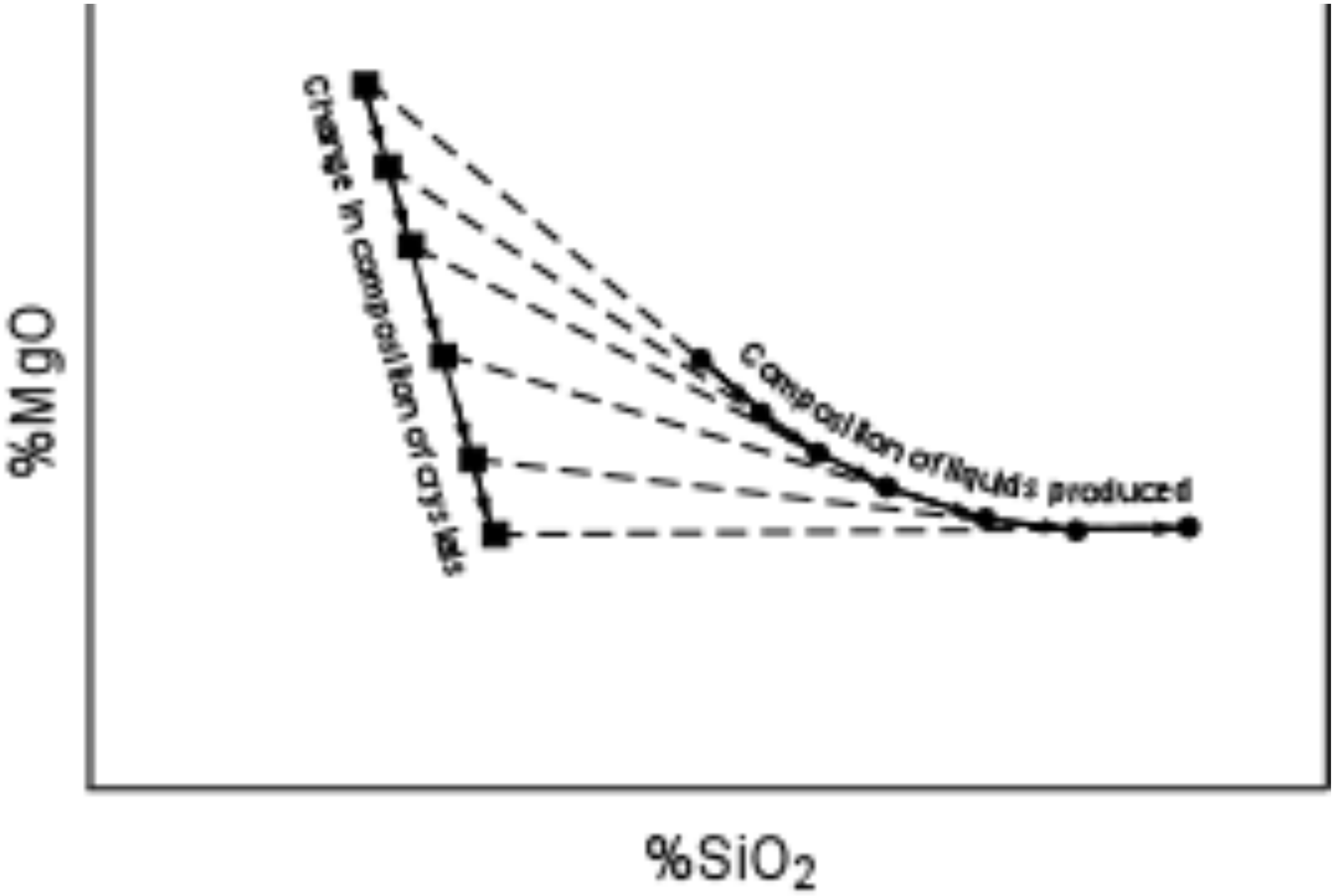


We would expect that with increasing SiO_2 oxides like MgO, and CaO should decrease with higher degrees of crystal fractionation because they enter early crystallizing phases, like olivines and pyroxenes.

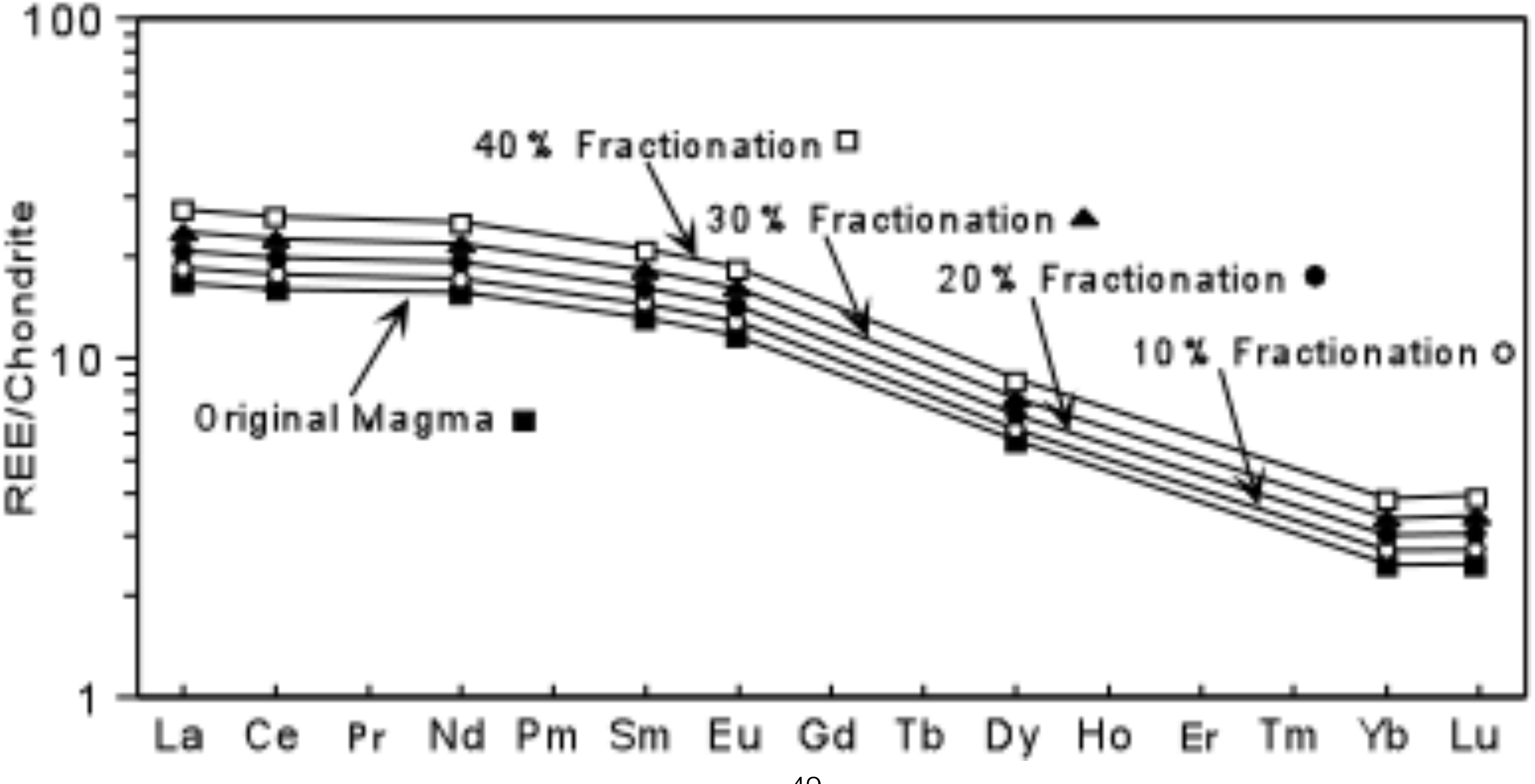
Oxides like H_2O, K_2O and Na_2O should increase with increasing crystal fractionation because they do not enter early crystallizing phases.

Furthermore, we would expect incompatible trace element concentrations to increase with fractionation, and compatible trace element concentrations to decrease.

This is generally what is observed in igneous rock suites.


Change in composition of crystals
Composition of liquids produced
%MgO
%SiO_2

Note that the REE patterns produced by higher percentages of crystal fractionation show higher concentrations, yet the patterns remain nearly parallel to one another.



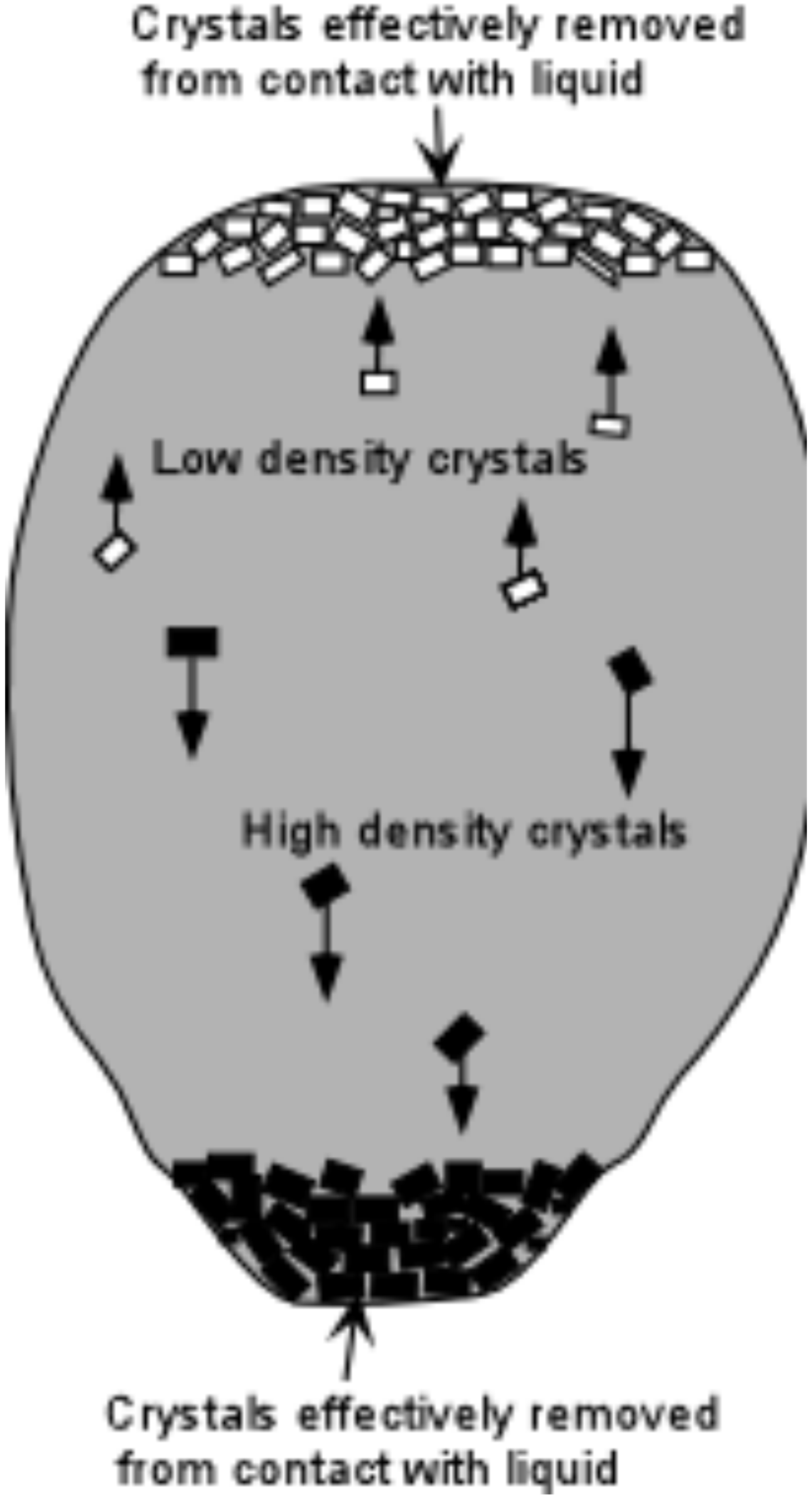
Mechanisms of Crystal Fractionation

Several mechanisms could operate in nature.

1. **Crystal Settling/Floating** – In general, crystals forming from a magma will have different densities than the liquid.

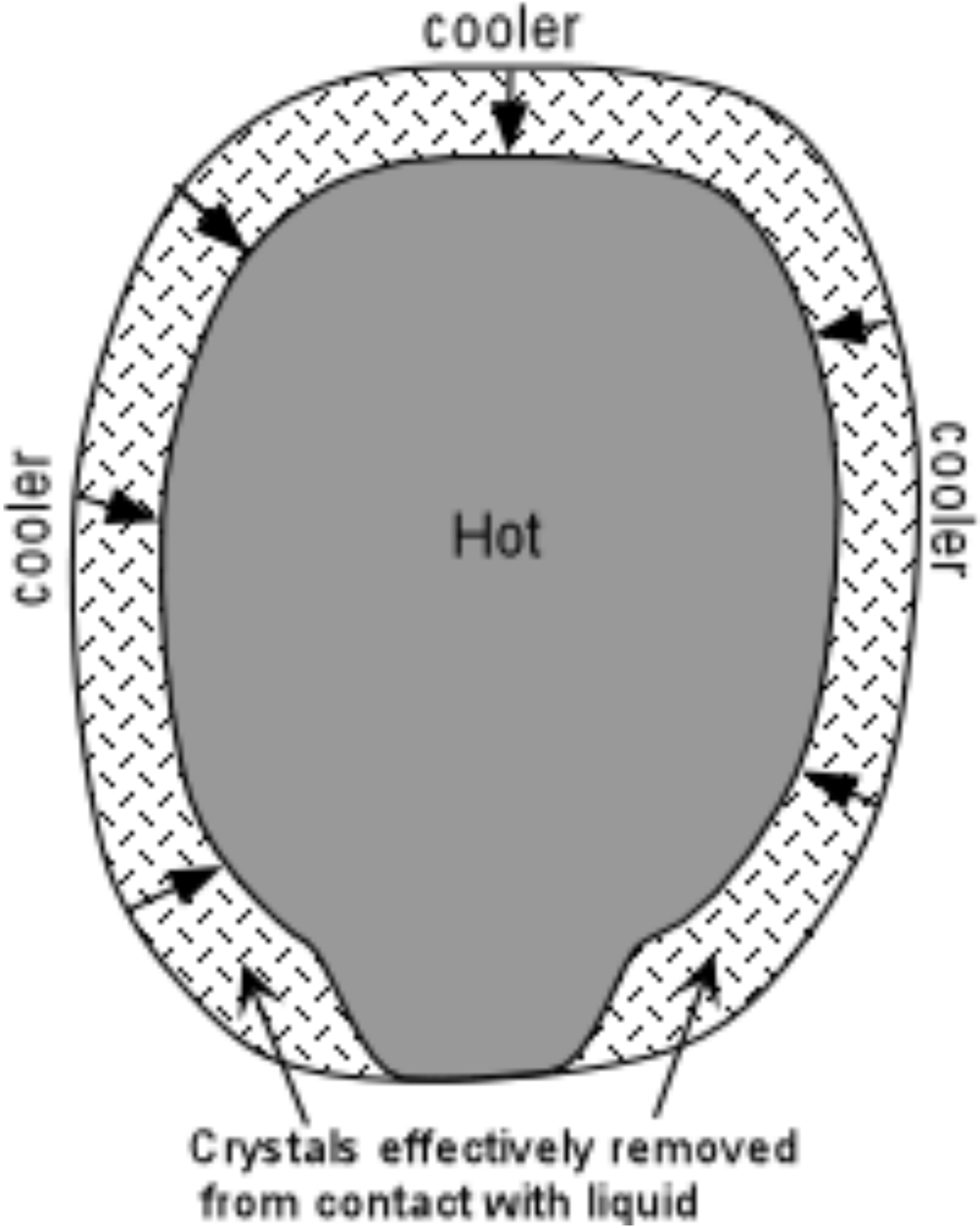
If the crystals have a higher density than the liquid, they will tend to sink or settle to the floor of the magma body. The first layer that settles will still be in contact with the magma, but will later become buried by later settling crystals so that they are effectively removed from the liquid.

If the crystals have a lower density in the magma, they will tend to float or rise upward through the magma. Again the first layer that accumulates at the top of the magma body will initially be in contact with the liquid, but as more crystals float to the top and accumulate, the earlier formed layers will be effectively removed from contact with the liquid.



2. **Inward Crystallization** – Because a magma body is hot and the country rock which surrounds it is expected to be much cooler, heat will move outward away from the magma. Thus, the walls of the magma body will be coolest, and crystallization would be expected to take place first in this cooler portion of the magma near the walls.

The magma would then be expected to crystallize from the walls inward. Just like in the example above, the first layer of crystals precipitated will still be in contact with the liquid, but will eventually become buried by later crystals and effectively be removed from contact with the liquid.


cooler
cooler
cooler
Hot
Crystals effectively removed from contact with liquid

3. **Filter pressing** – this mechanism has been proposed as a way to separate a liquid from a crystal–liquid mush. In such a situation where there is a high concentration of crystals the liquid could be forced out of the spaces between crystals by some kind of tectonic squeezing that moves the liquid into a fracture or other free space, leaving the crystals behind.

It would be kind of like squeezing the water out of a sponge.

4. Magma Mixing

If two or more magmas with different chemical compositions come in contact with one another beneath the surface of the Earth, then it is possible that they could mix with each other to produce compositions intermediate

There are several factors that would tend to inhibit mixing:

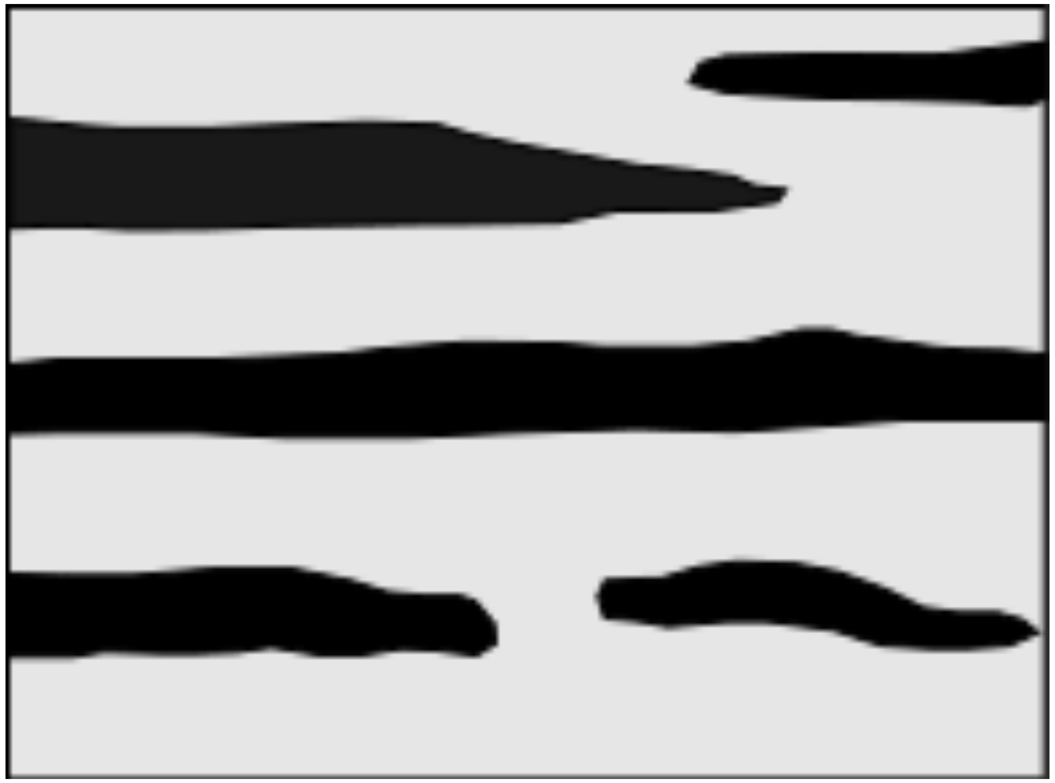
1. **Temperature** contrast – basaltic and rhyolitic magmas have very different temperatures. If they come in contact with one another the basaltic magma would tend to cool or even crystallize and the rhyolitic magma would tend to heat up and begin to dissolve any crystals that it had precipitated.

2. **Density** Contrast– basaltic magmas have densities on the order of 2600 to 2700 kg/m^3,

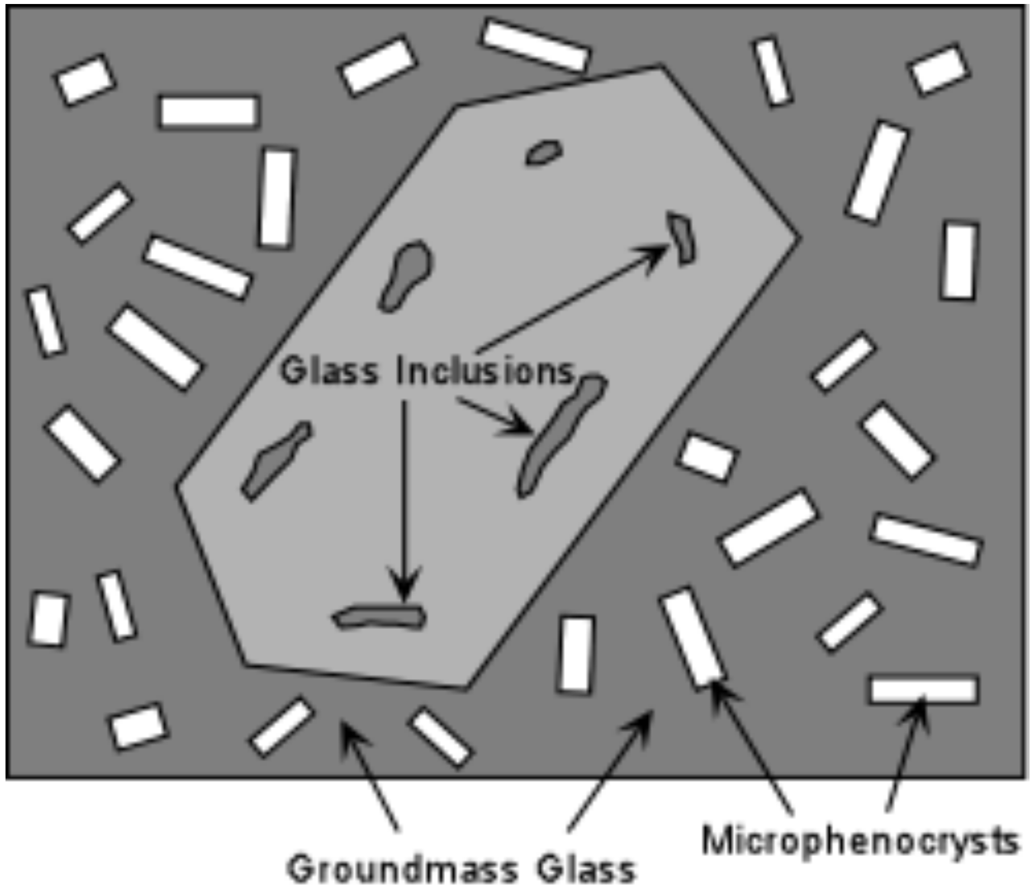
whereas rhyolitic magmas have densities of 2300 to 2500 kg/m^3. This contrast in density would mean that the lighter rhyolitic magmas would tend to float on the heavier basaltic magma and inhibit mixing.

3. **Viscosity** Contrast– basaltic magmas and rhyolitic magmas would have very different viscosities. Thus, some kind of vigorous stirring would be necessary to get the magmas to mix.

Evidence for Mixing

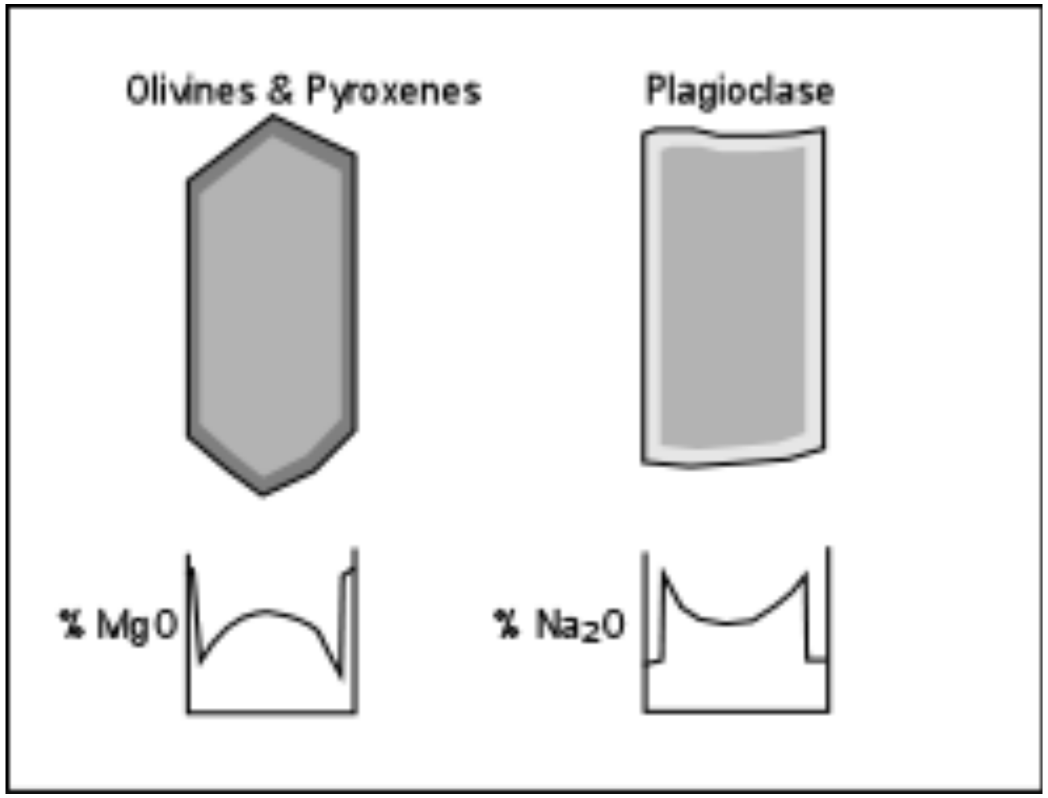


"marble cake" appearance, with dark colored mafic rock intermingled with lighter colored rhyolitic rock.



glass inclusions in the crystal

zoned crystals that show reversals of the zoning trends



5. Crustal Assimilation/Contamination

If the magma absorbs part of the rock through which it passes we say that the magma has become contaminated by the crust.

Either of these process would produce a change in the chemical composition of the magma unless the material being added has the same chemical composition as the magma.

a mixing, various stages of this process may be preserved in the magma and rock that results. Xenoliths (meaning foreign rock) are pieces of rock sometimes found as inclusions in other rocks.

Perhaps the best evidence of assimilation/contamination comes from studies of radiogenic isotopes.

5. Liquid Immiscibility

where liquids do not mix with each other

like in the alkali feldspar system, immiscibility is temperature dependent.

6. Combined Processes

magmas could mix and crystallize at the same time resulting in a combination of magma mixing and crystal fractionation.

Magmatic Ore Deposits

Mode of formation of magmatic ores:

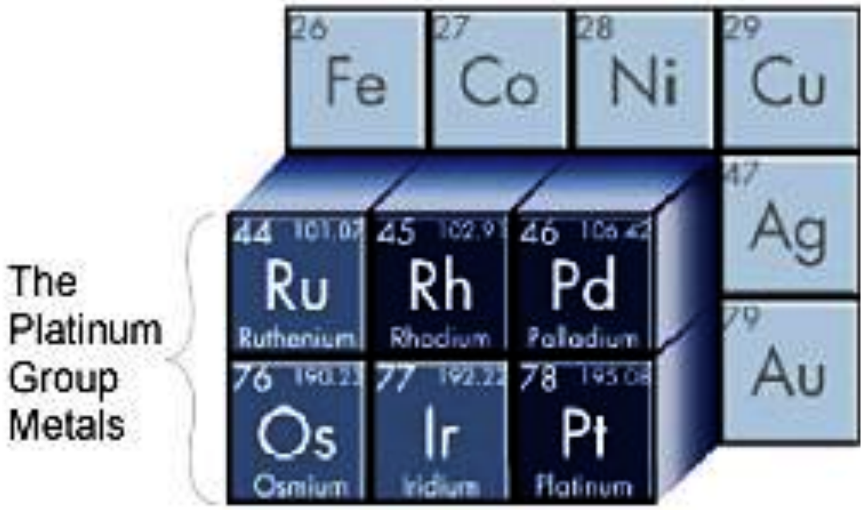
- fractional crystallization from melt
- liquid immiscibility between a sulfide liquid and the silicate melt.
- liquid immiscibility between an oxide liquid and the silicate melt
- liquid immiscibility between a carbonate liquid and the silicate melt

Magmatic Ore Deposits

- Dissemination involves simple crystallization whereby early formed crystals are found disseminated throughout the host‒ rock.
- End stages of magmatic crystallization.

Elements concentrated by magmatic processes:

- PGM, Ni, Cu, Ti, V, Cr, diamonds, minor Fe
- REE, Nb, Zr, Li, Be, B, U, W, Sn, and Ta.



The most important magmatic deposits are restricted to **mafic and ultramafic** rocks which represent the crystallization products of basaltic or ultramafic liquids.

Association of Rocks and ore deposits:

1. Chromite peridotites, anorthosites and similar mafic rocks.
2. Platinum Group Metals (PGM) norite, peridotite or their alteration products.
3. Cu–Ni sulfides associated with norite
4. Fe–Ti oxides found with gabbros and anorthosites.
5. Diamond in kimberlites
6. REE, and Zr in carbonatites
7. Pegmatites with granitic rocks.

1. Chromite Deposits

The processes involved in the formation of chromite layers are fractional crystallization and gravity settling.

Chromite crystallizes into mineral grains within the silicate liquid and, because they are heavier than the liquid, they sink to form a cummulate layer at the base of the intrusive.

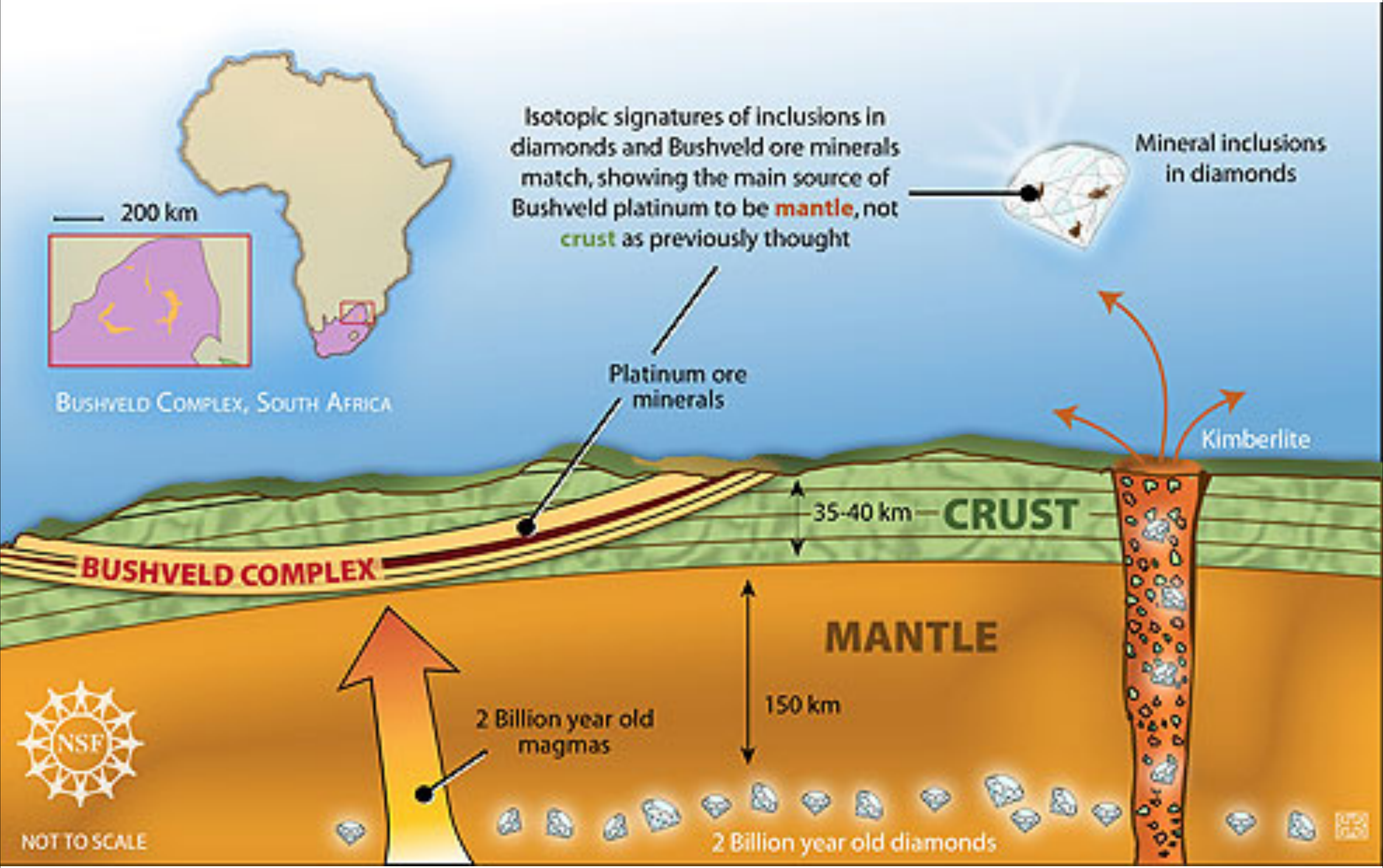
There are two main types of chromite deposits:

1. Stratiform and
2. Podiform.

a. **Stratiform** chromite deposits consist of laterally persistent chromite-rich layers (a few mm to several m thick) alternating with silicate layers.

* The silicate layers include ultramafic and mafic rocks such as dunite, peridotite, pyroxenite and a variety of others, less commonly gabbroic rocks.

* They are found in Archean age such as the **Bushveld Complex in South Africa**.


200 km
Bushveld Complex, South Africa
Isotopic signatures of inclusions in diamonds and Bushveld ore minerals match, showing the main source of Bushveld platinum to be mantle, not crust as previously thought
Mineral inclusions in diamonds
Platinum ore minerals
Kimberlite
35-40 km
CRUST
BUSHVELD COMPLEX
MANTLE
150 km
2 Billion year old magmas
NSF
NOT TO SCALE
2 Billion year old diamonds

b. **Podiform** chromite deposits irregularly shaped massive chromite bodies and they are predominantly found within dunitic (olivine-rich) portions of ophiolite complexes.

* The rocks associated with podiform chromites are generally referred to as "**Alpine-type**" **peridotites** and they are usually found along major fault zones within mountain belts.

2. Ni-Cu Deposits

* Ni-Cu Deposits are the end of a magmatic process known as "**liquid immiscibility**"

This process involves the separation from the parental magma of a sulphur-rich liquid containing Fe-Ni-Cu.

* Upon cooling, the sulphur-rich liquid produces an immiscible sulphide phase (droplets of sulphide liquid in silicate liquid, like oil in water) from which minerals such as pyrrhotite (FeS), pentlandite $(Fe,Ni)_9S_8$, and chalcopyrite ($CuFeS_2$) crystalize.

* Typical magmatic Ni–Cu deposits tend to occur at or near the base of their intrusive hosts.
because

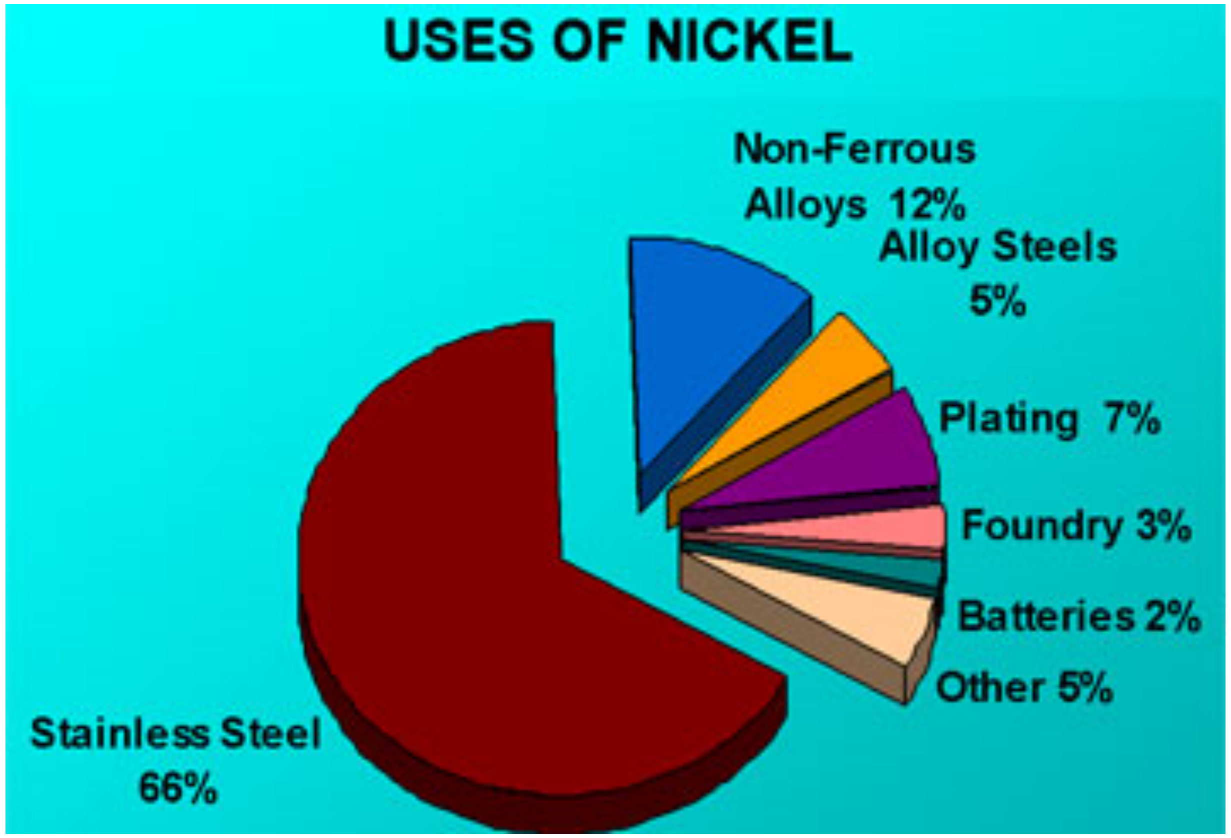
a. immiscible sulphide liquids are heavier than silicate liquids and therefore sink to the bottom of the magma chamber and

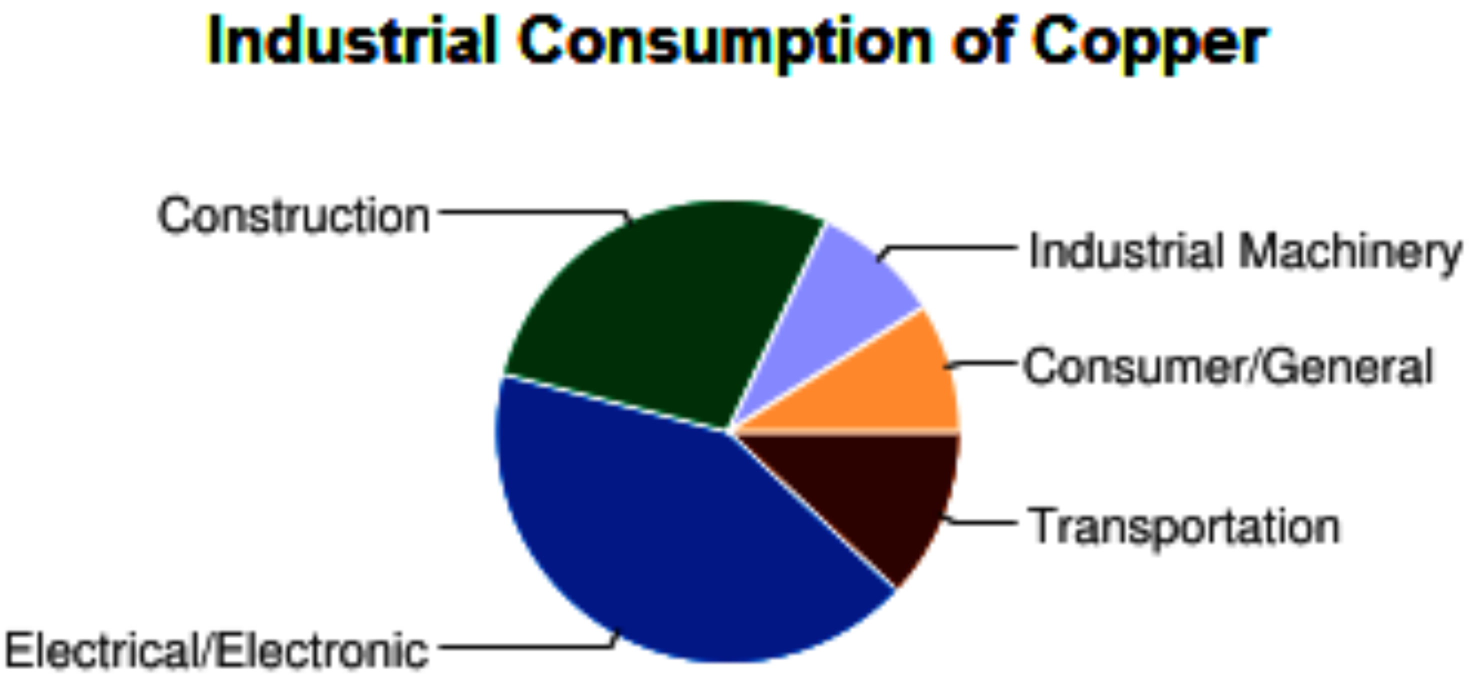
b. without the presence of sulphur, metals such as Ni become incorporated into silicate crystal structures, such as pyroxene.

* The largest deposits are of **Archean and Proterozoic age**.

Uses of Chromite:

1. Steel industry
2. Refractory
3. Chemical industries





3. Platinum Group Metals PGM

The six **platinum–group metals** are ruthenium, rhodium, palladium, osmium, iridium, and **platinum**.

They occur at or near the base of complexely differentiated gabbro–dolerite intrusions (50 to 350 m thick) as a residual liquid injection.

Emplaced during **late Permian to Triassic time during rifting of the Siberian platform**.

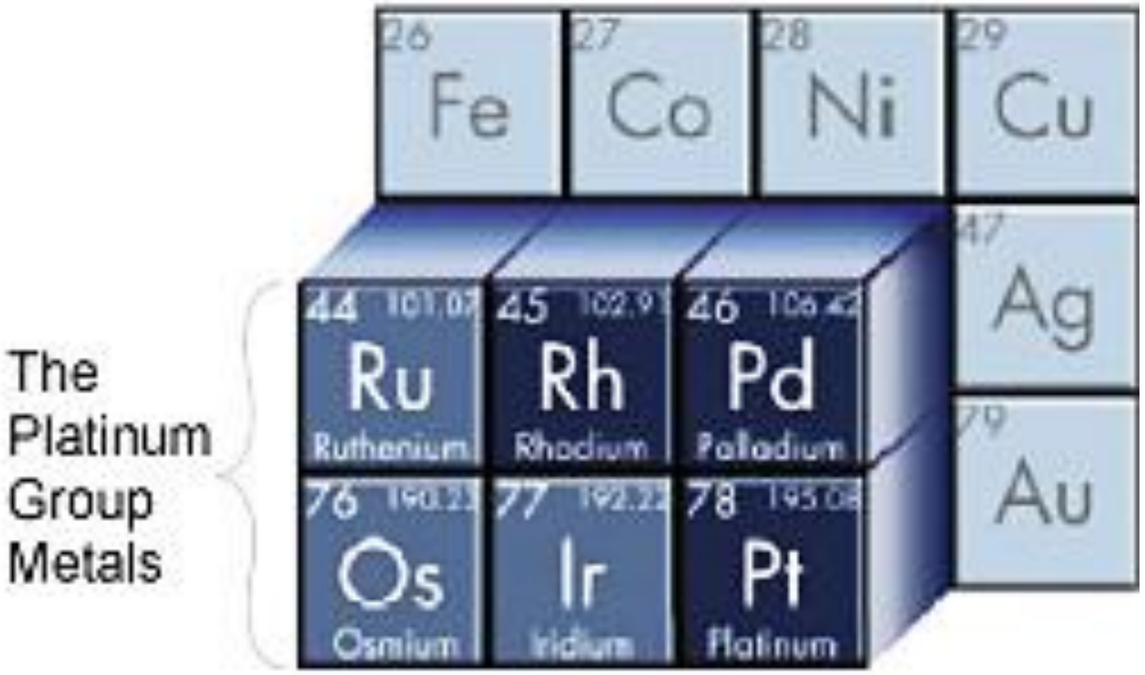
The mineralogy of the ores include pyrrhotite, chalcopyrite, pentlandite and a great variety of PGM minerals.

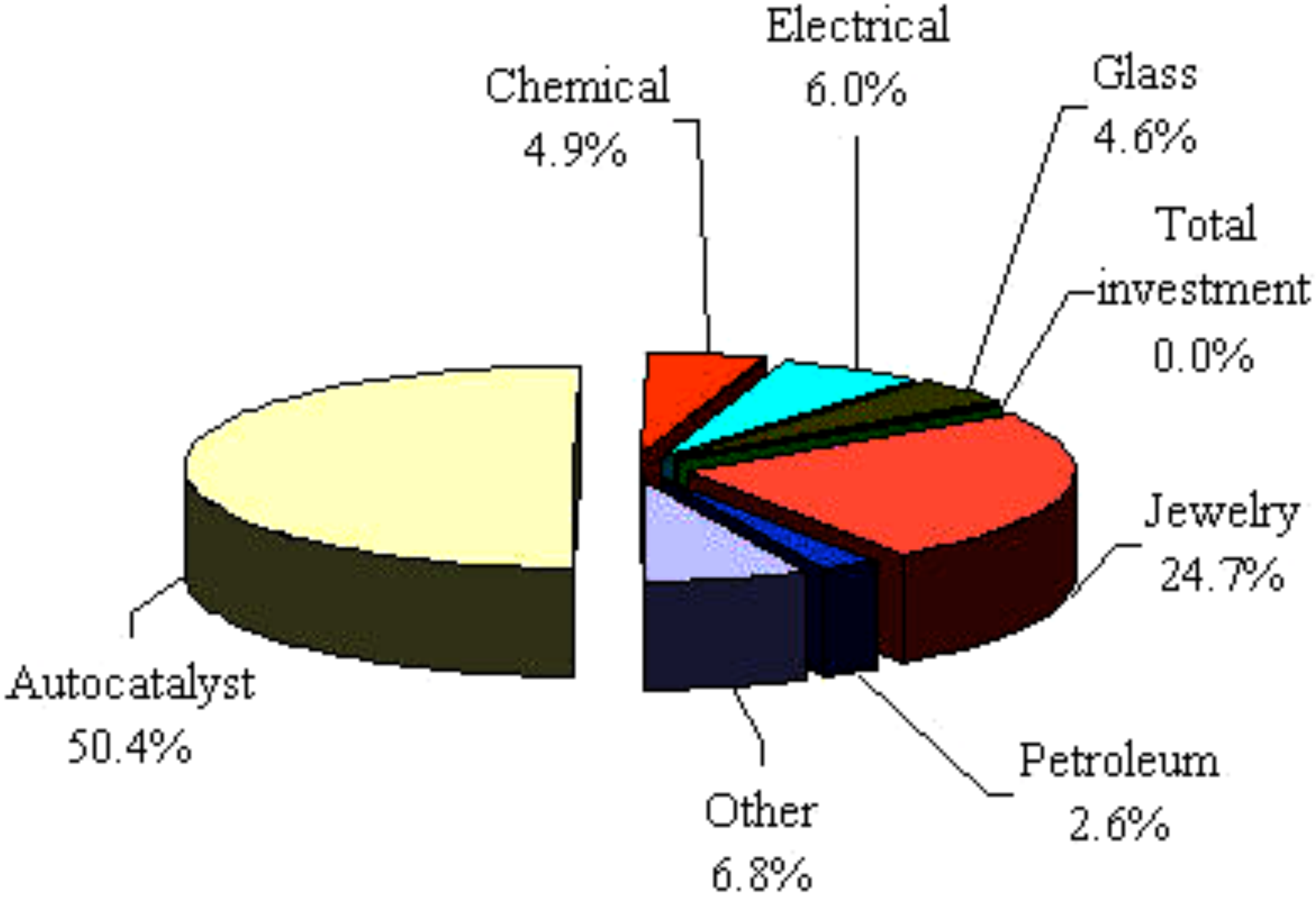
The metasomatic dunite pipes of the Bushveld Complex played a significant role as high–grade platinum producers during the early days of platinum mining in South Africa.

Appreciable PGM values are characterized by:

1. Pegmatitic texture

2. The presence of hydrous minerals within otherwise anhydrous layered successions.


26
Fe
27
Co
28
Ni
29
Cu
47
Ag
79
Au
The Platinum Group Metals
44 101.07
Ru
Ruthenium
45 102.91
Rh
Rhodium
46 106.42
Pd
Palladium
76 190.23
Os
Osmium
77 192.22
Ir
Iridium
78 195.08
Pt
Platinum


Electrical 6.0%
Chemical 4.9%
Glass 4.6%
Total investment 0.0%
Jewelry 24.7%
Petroleum 2.6%
Other 6.8%
Autocatalyst 50.4%

Hydrothermal Ore deposits

Any concentration of metallic minerals formed by the precipitation of solids from hot mineral water (hydrothermal solution).

Hot water or “hydrothermal fluids” pass through a nearby igneous rocks fractures or porous spaces within the rock, altering the chemical composition.

This chemical alteration can be the result of “**adding**, **removing**, or the **redistribution** of the chemical components”.

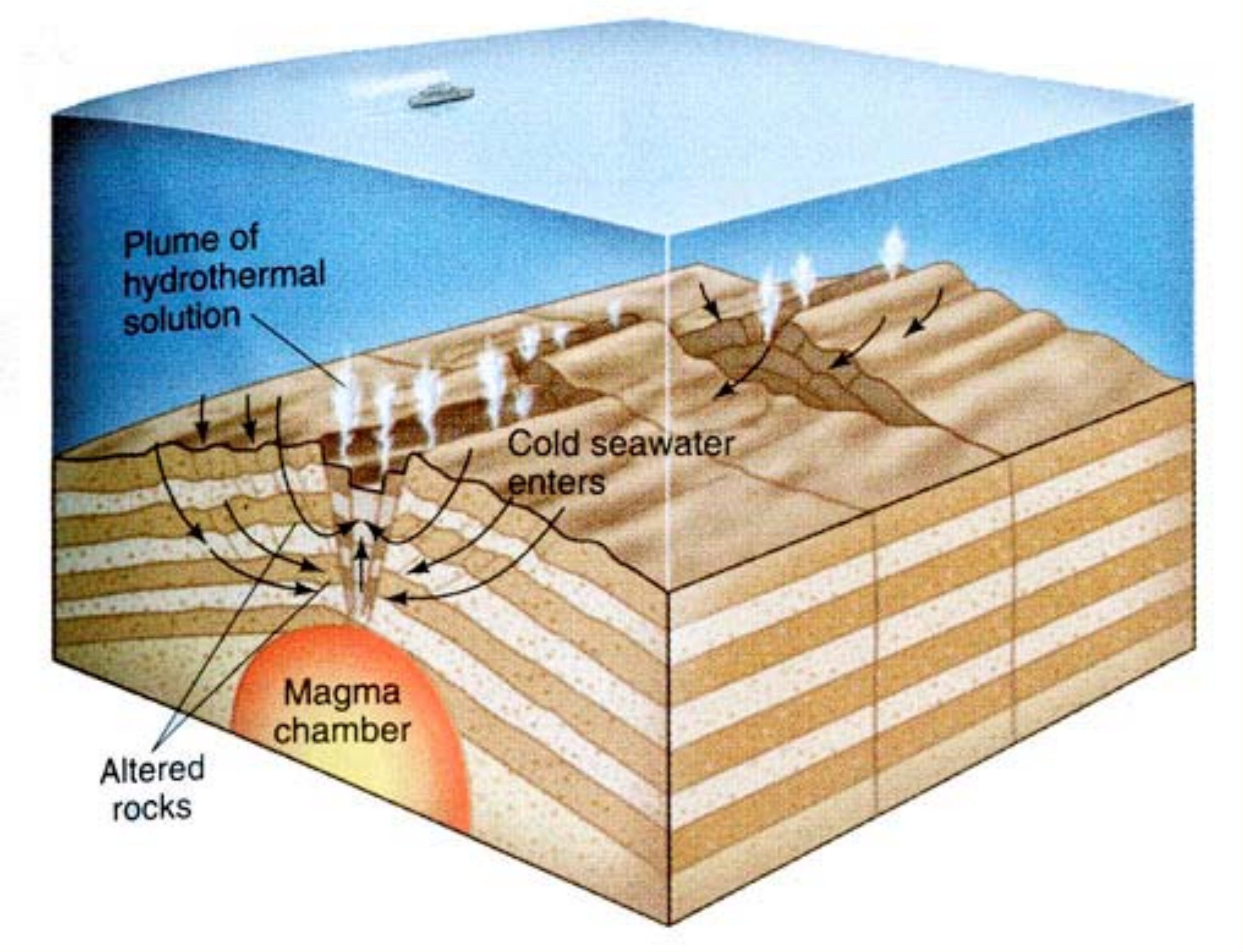
Conditions necessary for the formation of hydrothermal mineral deposits include:

(1) presence of hot water to dissolve and transport minerals, heated by **a**. **nearby magma** or by **b**. **energy released by radioactive decay** or by **c**. **faulting** of the Earth’s crust.

(2) presence of interconnected openings in the rock to allow the solutions to move,

(3) availability of sites for the deposits, and

(4) chemical reaction that will result in deposition.



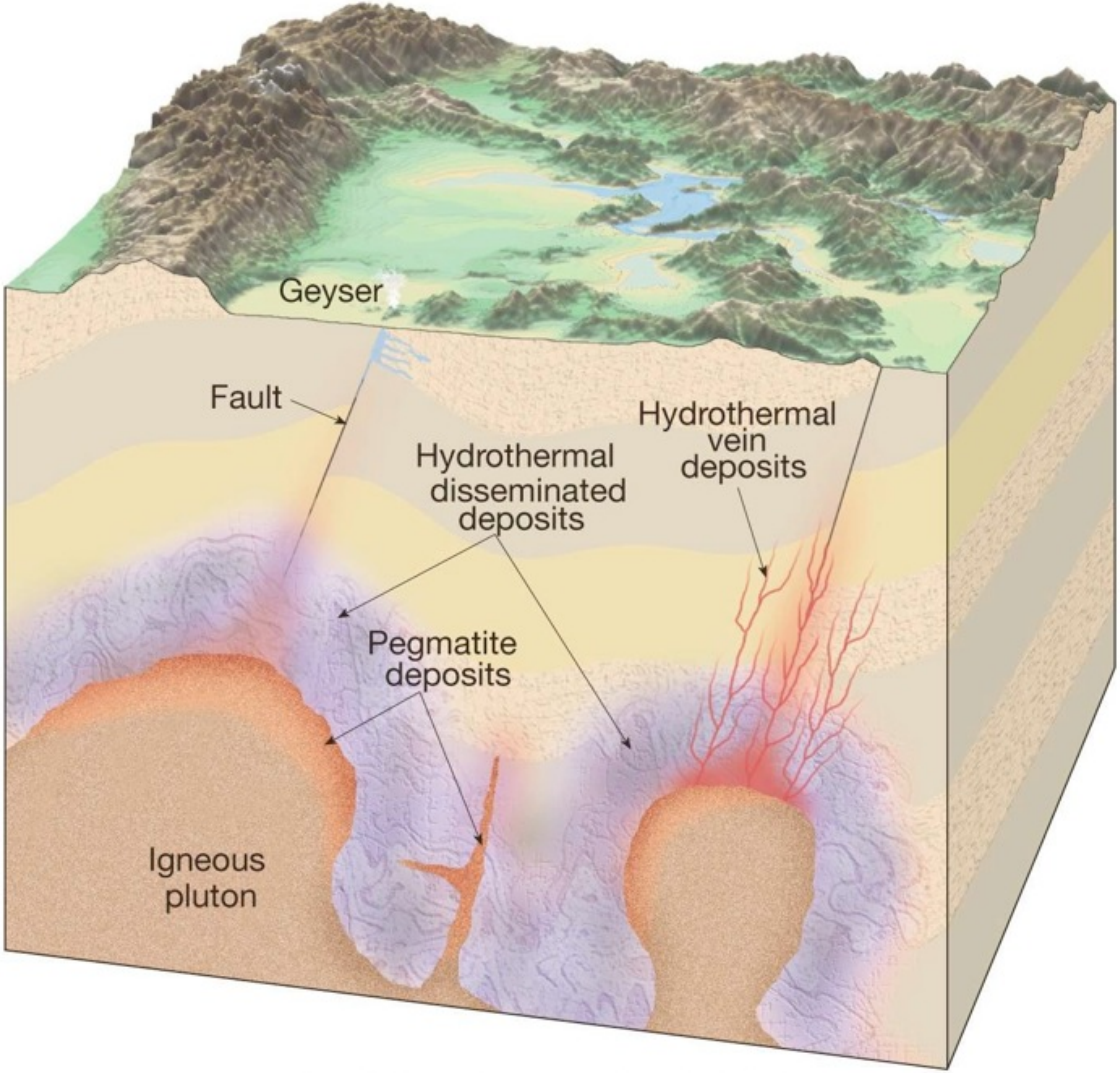
An example of a hydrothermal system and its circulation. From "The Blue Planet" by Brian J. Skinner (1995). Also taken from Williams, Curtis "Hydrothermal Alteration and Mineral Deposits." (2002).

Typically, these “hydrothermal fluids” or “aqueous solutions” carry many metals in addition to “silicates and other non-metallic materials”.

When the water that is heated will alters the nearby igneous rocks, the hydrothermal solution then becomes mineral rich.

This mineral-rich solution rises, meandering its way through fractures or cracks in the rock as it moves and dissolving other minerals on its path.

once this solution has cooled in the fracture of the rock- creating **veins**.


Geyser
Fault
Hydrothermal vein deposits
Hydrothermal disseminated deposits
Pegmatite deposits
Igneous pluton

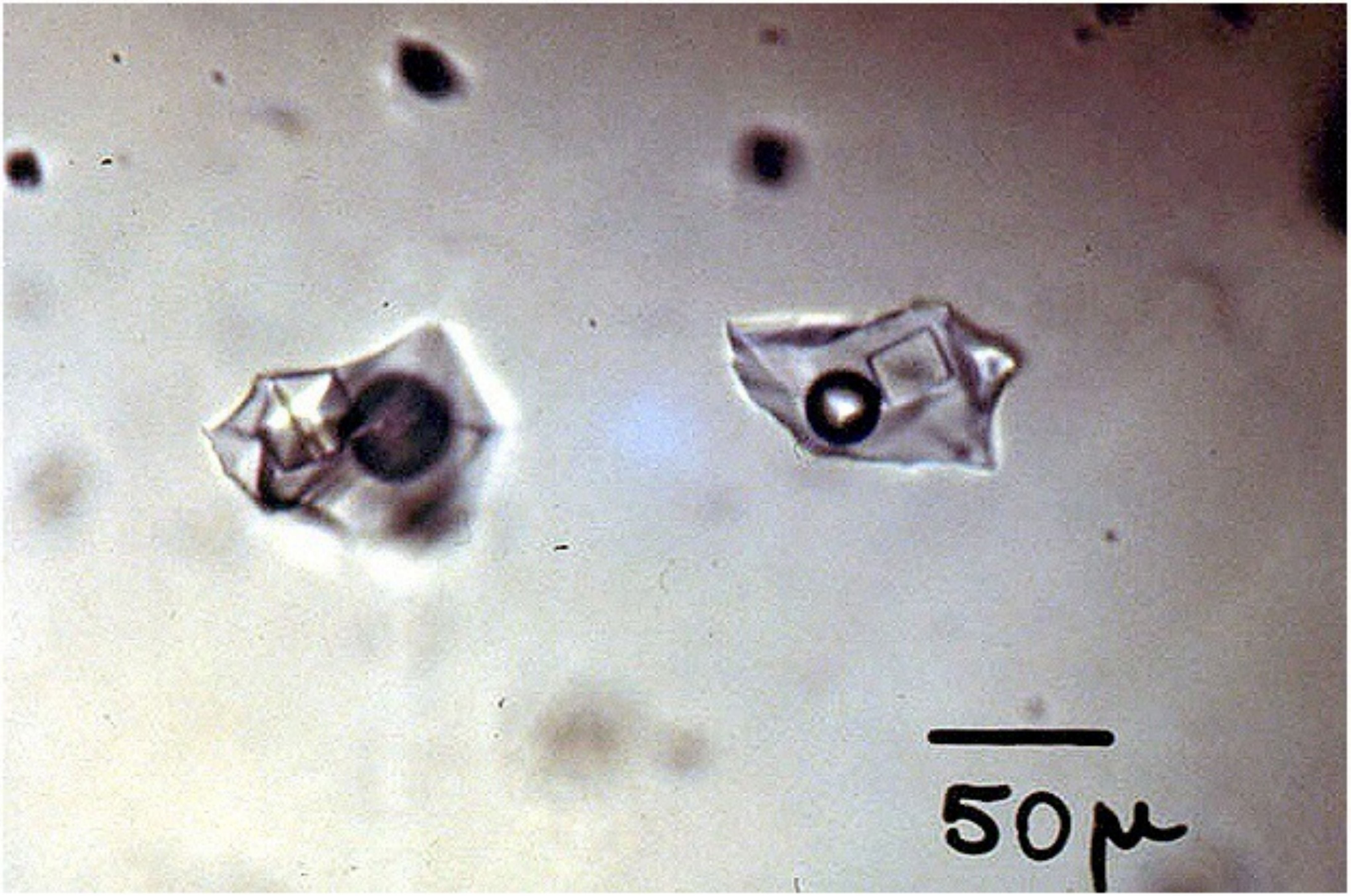
Evidence for the existence of modern hydrothermal fluids include

(1) geysers and hot springs, and

(2) hot fluids sampled in deep drill holes.

(3) fluid inclusions in minerals (i.e. microscopic droplets of fluid enclosed by growing crystals;

(4) rock fabrics that indicate high–temperature chemical reactions between fluid and minerals


50µ


Vein deposit

Hydrothermal solutions have a wide variety of chemical compositions:

- Solvent H_2O
- Major anions Cl^-, HCO^{3-}, HS^- or $SO4^{2-}$
- Major cations Na^+, Ca^{2+}, K^+, Fe^{2+}, Mg^{2+}
- Neutral species CO_2, CH_4, H_2S, N_2, H_4SiO_4
- pH strongly acid (pH ≈ 2) to strongly basic (pH ≈ 12)
- Redox state oxidising (e.g. hematite stable) or reducing (e.g. native Cu)

Total dissolved chemical species: up to 60–70 mass%

Main factors for development of hydrothermal ore deposition include:

- water source, heated up to 900 °C under high pressure (up to many thousands of bars)
- source of ore components, and
- transport of ore constituents, flow paths may be tens of km long, both vertically and horizontally.
- permeability, cause, and
- ore deposition.

Each of these factors strongly influences the hydrothermal process.

The main sources of water include:

- “surface water,
- groundwater,
- meteoric waters,
- sea water,
- connate water or water enclosed in the rocks at the time of formation,
- metamorphic water; and,
- magmatic water.

Meteoric waters can be collected from precipitation factors such as snow, rain, etc;

Formation water that has been trapped with a specific area; such as pores of sediments.

This water will eventually become highly concentrated with minerals and metals that it dissolves as it moves through the igneous rocks.

The energy behind the hydrothermal alteration process is the **“geothermal cell”**.

A “geothermal cell” is the place in which the water is heated.

Typically, the hydrothermal solutions have a high saline content; therefore the movements of these fluids alter the rock.

With the minerals varying conditions: temperature, pressure, pH and Eh if the conditions change a condition will therefore change. This may then cause the rock to react with nearby materials.

The temperatures at which the minerals are formed range from 50 to 650°C.” These highly varying temperatures create for a highly conducive altering agent.

“The movement of these hydrothermal fluids in the crust of the Earth is known as **“hydrothermal convection**.

Hydrothermal Ore Formation

The formation of hydrothermal ores is attributed to the hydrothermal solution or fluids that filter metals and minerals from the rock.

These metals are then deposited into fracture and cracks within the rock called: **veins**.

Fractures are a result of things such as;

a. water freezing and expanding.

b. seismic activity, when the ground shifts fractures and fissures are left in the bedrock and other components that make up the crust.

The hydrothermal fluids, easily carry the highly concentrated metals these metallic ions are typically transported is through **“complex ions”**

These complex ions prevent deposition of the metal during the move. In contrast, the simple ions easily loose the metal during the transport.

Permeability plays a key role in the movement of the hydrothermal solutions.

Deposition of the ore minerals is usually due to

(1) temperature decrease– cooling,

(2) decrease in pressure,

(3) change in composition of hydrothermal solutions by **reaction** with the wall rock along their flow paths (e.g. acid neutrlisation).

These 3 processes super–saturate the fluids with respect to the dissolved minerals, and hence cause **mineral precipitation** (according to their relative solubilities)

Deposition of the ore can be sub aerial, seafloor, found in a fracture, or a rock.

Mineral **zoning** patterns often times develop near ore deposits as a result of changes in temperature, the chemical composition of the fluid, and gas content.

Many economically important mineral deposits (i.e. ore deposits) are of hydrothermal origin, e.g. **sulphides** of Cu, Pb, Zn, Fe, Mo; **oxides** of Fe, Sn, W, U; **native** Au, Ag; magnesite, siderite, barite, talc …

Hydrothermal Rocks

Rocks which form by

(1) mineral precipitation from hydrothermal fluids or by

(2)fluid–mineral interactions are called **hydrothermal rocks**:

Forms of deposition

1. **hydrothermal vein rocks**: hydrothermal minerals may precipitate in open cavities with sequential crystallization fabrics.

- most common hydrothermal minerals precipitated in veins are those with high aqueous solubilities
  - Common hydrothermal vein minerals are: **quartz**, **carbonates**, **sulphides**, **fluorite**, **sulphates**.

2. Hydrothermal minerals may precipitate via reactions that **replace** pre-existing minerals in older magmatic, sedimentary or metamorphic wall rocks

Replacement minerals often contain some elements from the original wall rock and some elements from the hydrothermal solution, e.g.:

Magmatic feldspar in granite + Acid in hydrothermal fluid

⇓

Hydrothermal muscovite + Cation dissolved in hyd. fluid + hyd. Quartz

$3KAlSiO + 2H^{+}$ " $KAl(AlSiO)(OH) + 2K^{+} + 6SiO_{38}(aq)$

- Often the original crystal habits of the replaced minerals are copied by **finegrained aggregates** of the new hydrothermal minerals

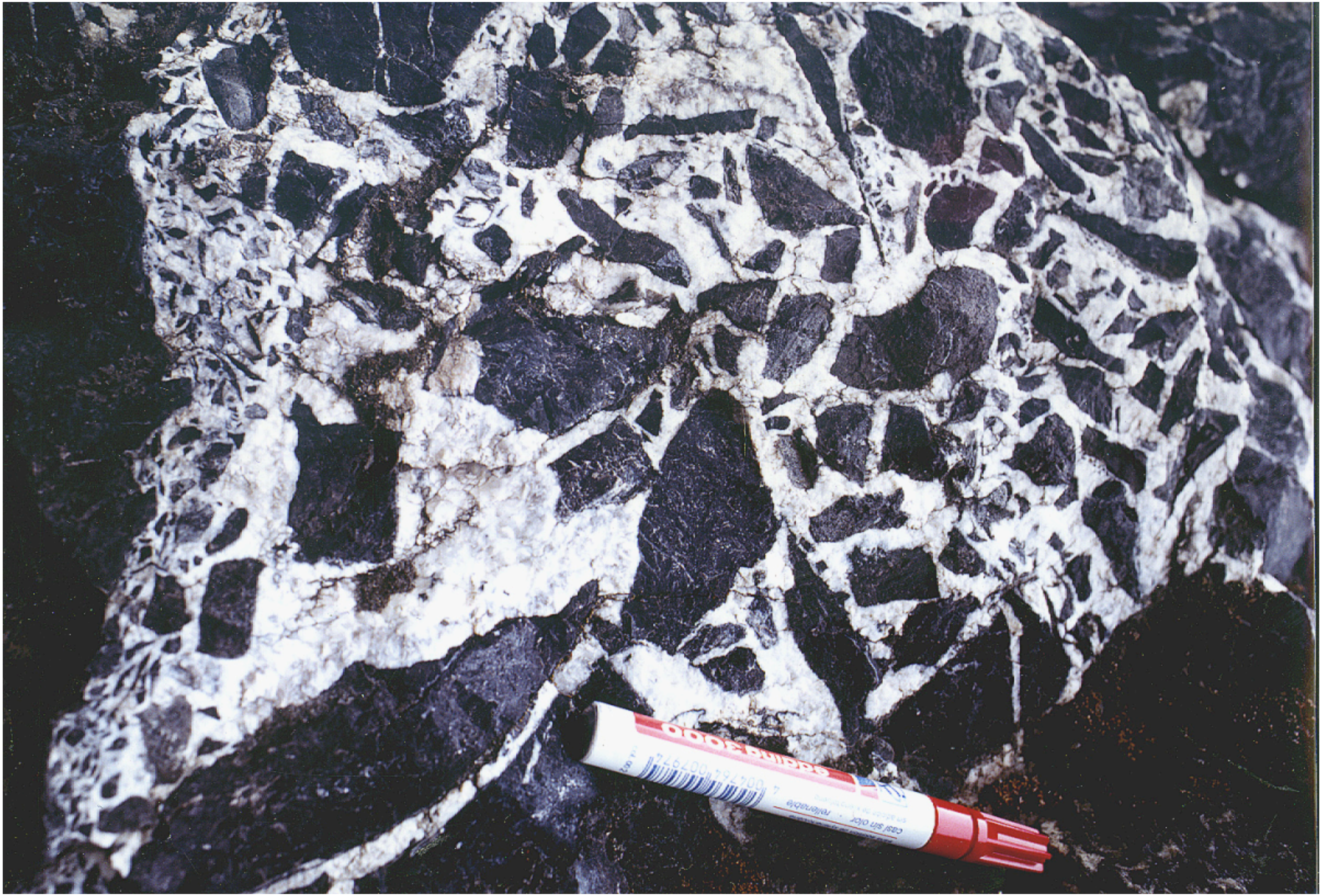
- Common replacements minerals are: **clays, micas, chlorite, pyrite, carbonate**
- Older rocks modified by reaction with hydrothermal fluids are said to be **hydrothermally altered** (e.g. "hydrothermally altered basalt")

Mississippi Valley-Type Lead-Zinc Deposits (MVt)

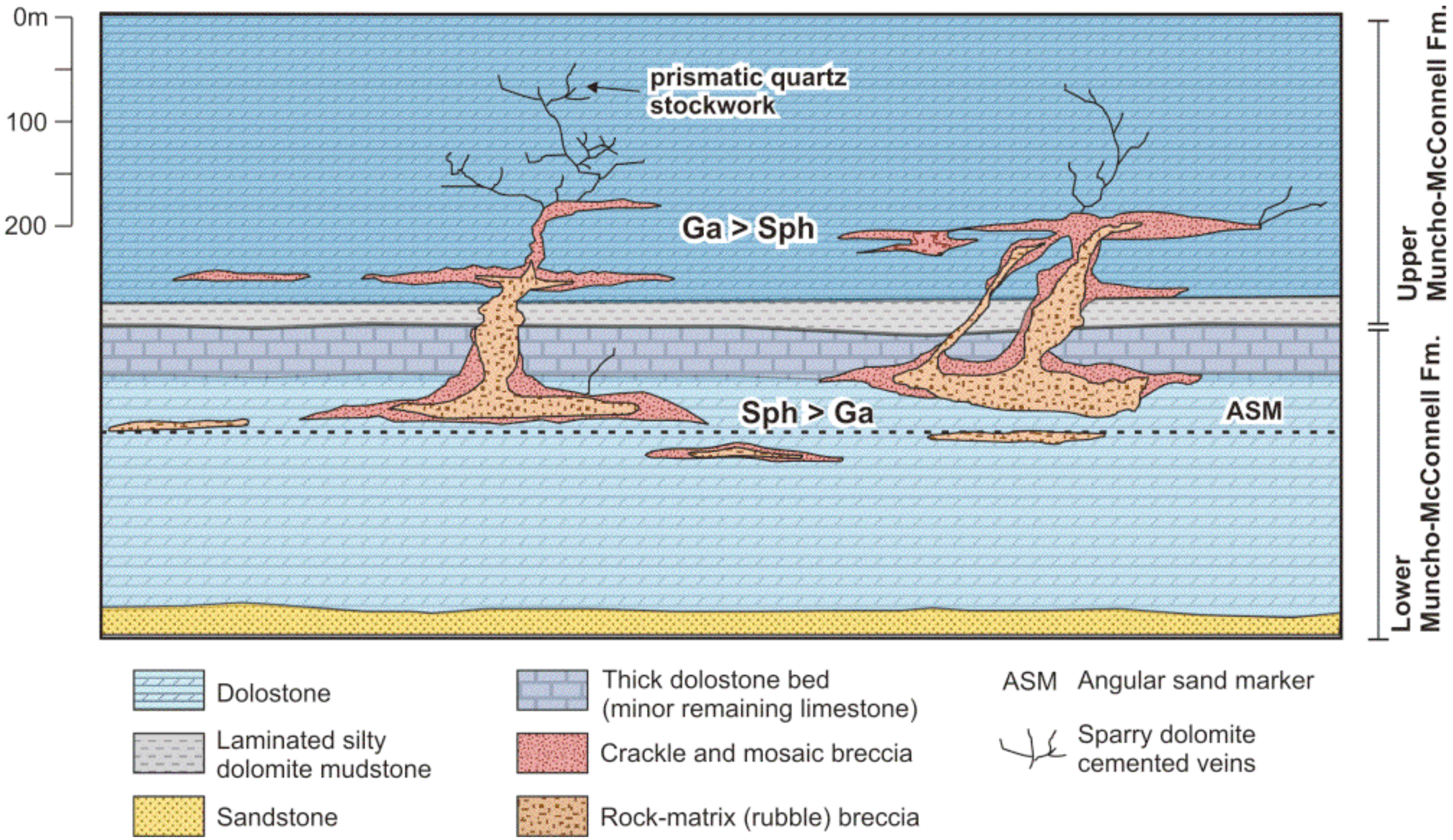
- MVT deposits are **sulphide bodies**, composed predominantly of zinc and lead, bound in sphalerite and galena.
- The deposits are hosted in **carbonate rocks**, usually dolostone and less frequently limestone. The dolostone consists of medium to coarse-grained white sparry dolomite that has replaced a fine-grained dolostone host, which itself has replaced a limestone host.
- Sulphide textures are mostly related to **open-space filling** of **breccias**, fractures, and vugs

Most MVT deposits show features of hydrothermal brecciation, recrystallization, dissolution, dolomitization and silicification.

Deposits formed from hot to warm, saline, aqueous solutions (similar to oil–field brines) that migrated out of sedimentary basins, through aquifers, to the basin periphery and into the platform carbonate sequences.



hydrothermal breccia


0m
100
200
prismatic quartz stockwork
Ga > Sph
Sph > Ga
ASM
Upper Muncho-McConnell Fm.
Lower Muncho-McConnell Fm.
Dolostone
Laminated silty dolomite mudstone
Sandstone
Thick dolostone bed (minor remaining limestone)
Crackle and mosaic breccia
Rock-matrix (rubble) breccia
ASM Angular sand marker
Sparry dolomite cemented veins

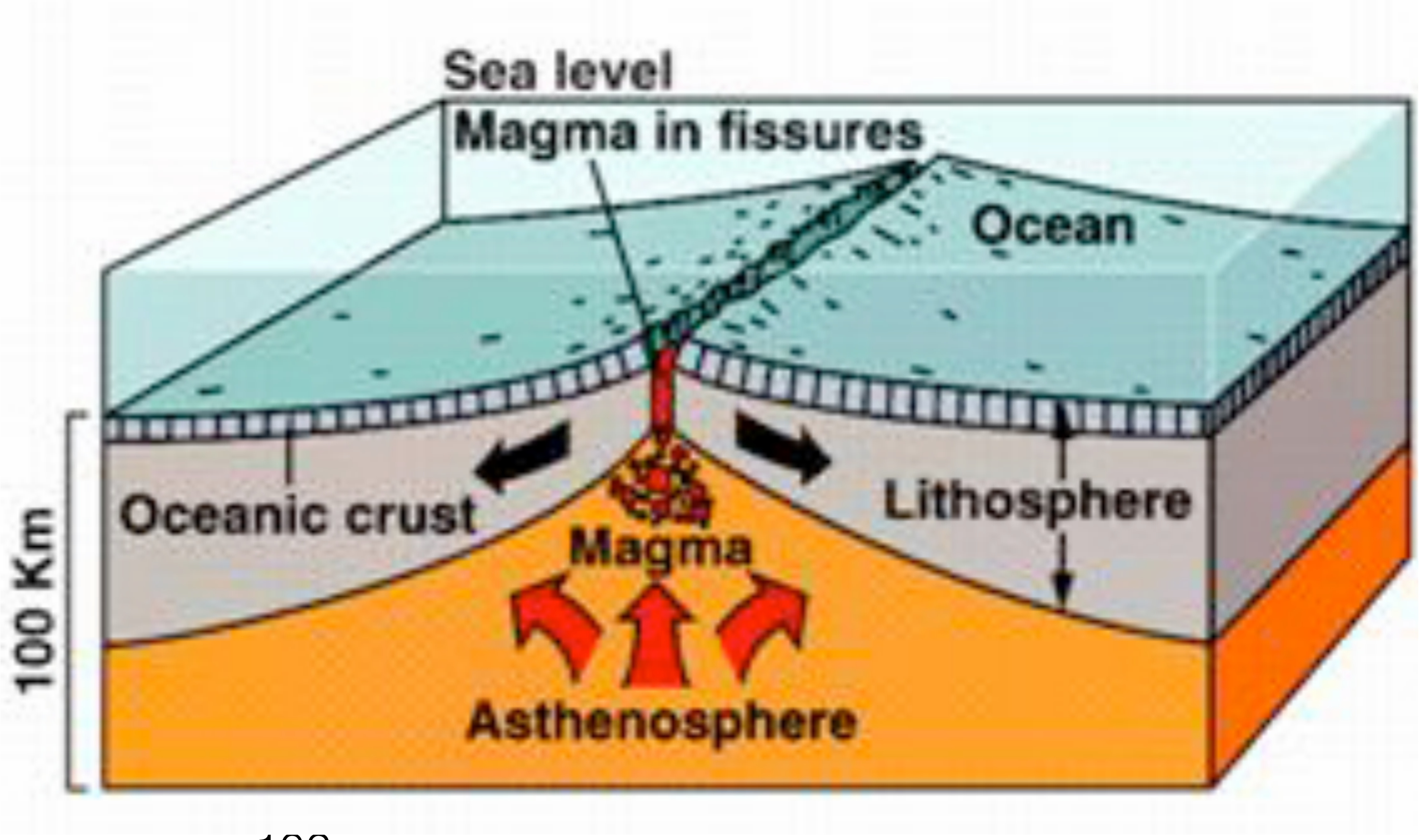
Seafloor Hydrothermal Deposits

Mid–oceanic ridges (MOR) are sites where new oceanic crust forms by crystallization of basaltic (gabbroic) magmas fed by upwelling asthenosphere.

MOR are also sites of vigorous hydrothermal activity:

- Deep fractures form in new oceanic crust due to shrinkage of lavas and movement of transform faults. **Seawater** penetrates these interconnected fractures to depths of 2 – 4 km, due to the **hydralic gradient** imposed by the overlying ocean

- Magmatic activity imposes strong **thermal gradients** perpendicular to the spreading ridges (high T at MOR, low T further away from MOR). These gradients cause **seawater convection** through the fractures (i.e. multi-pass fluid flow). The amount of convected seawater world-wide ≈ 10^{14} kg / year.



- Descending, cold, oxidising, $SO4^{2-}$–rich seawater is heated by the nearby magmatic rocks as it flows towards the high–temperature site.

- The hot seawater racts with the magmatic rocks, causing:

– reduction of the fluid, e.g. $SO4^{2-}(aq) \rightarrow H_2S(aq)$

– hydration of magmatic minerals

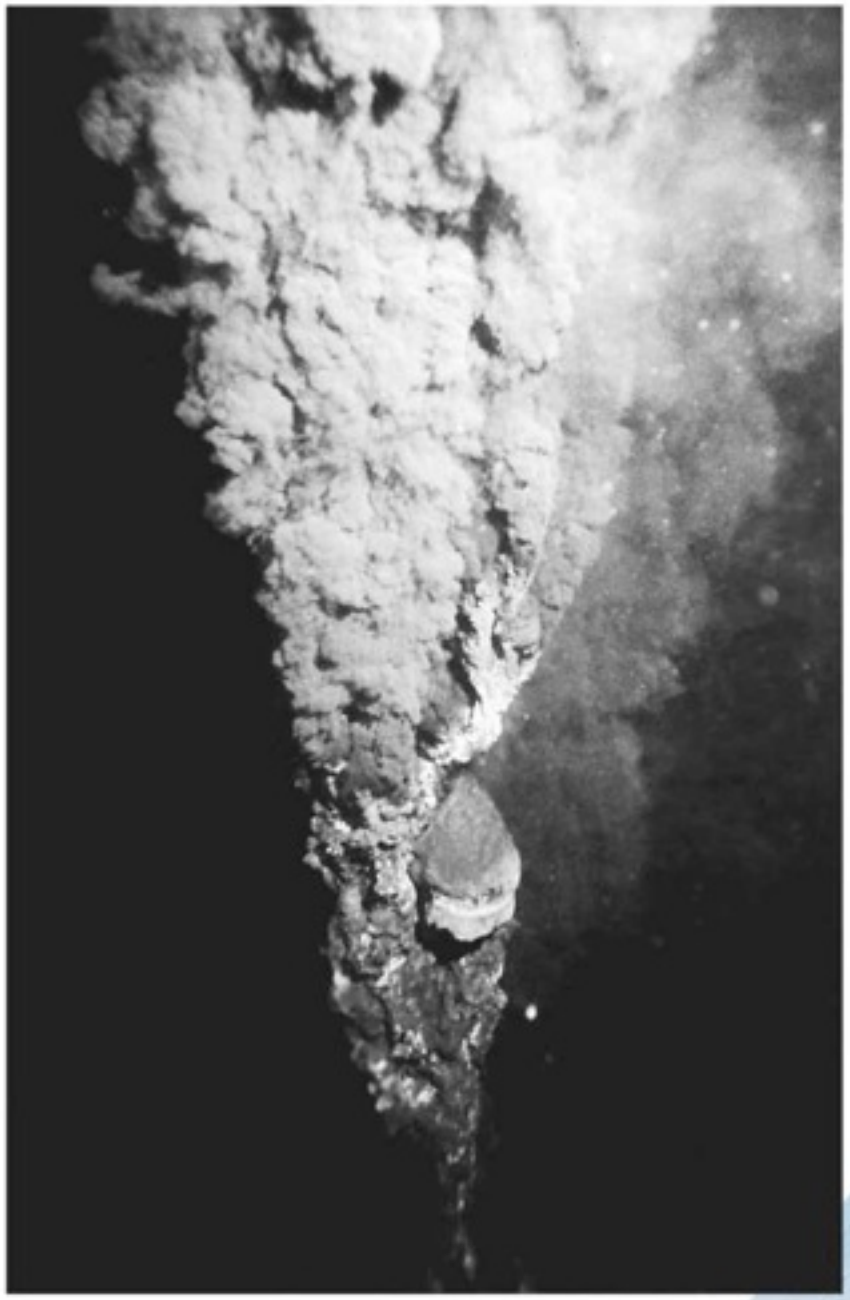
– exchange of chemical components, e.g. fluid donates Mg and Na to basalt; basalt donates Ca and Si to fluid)

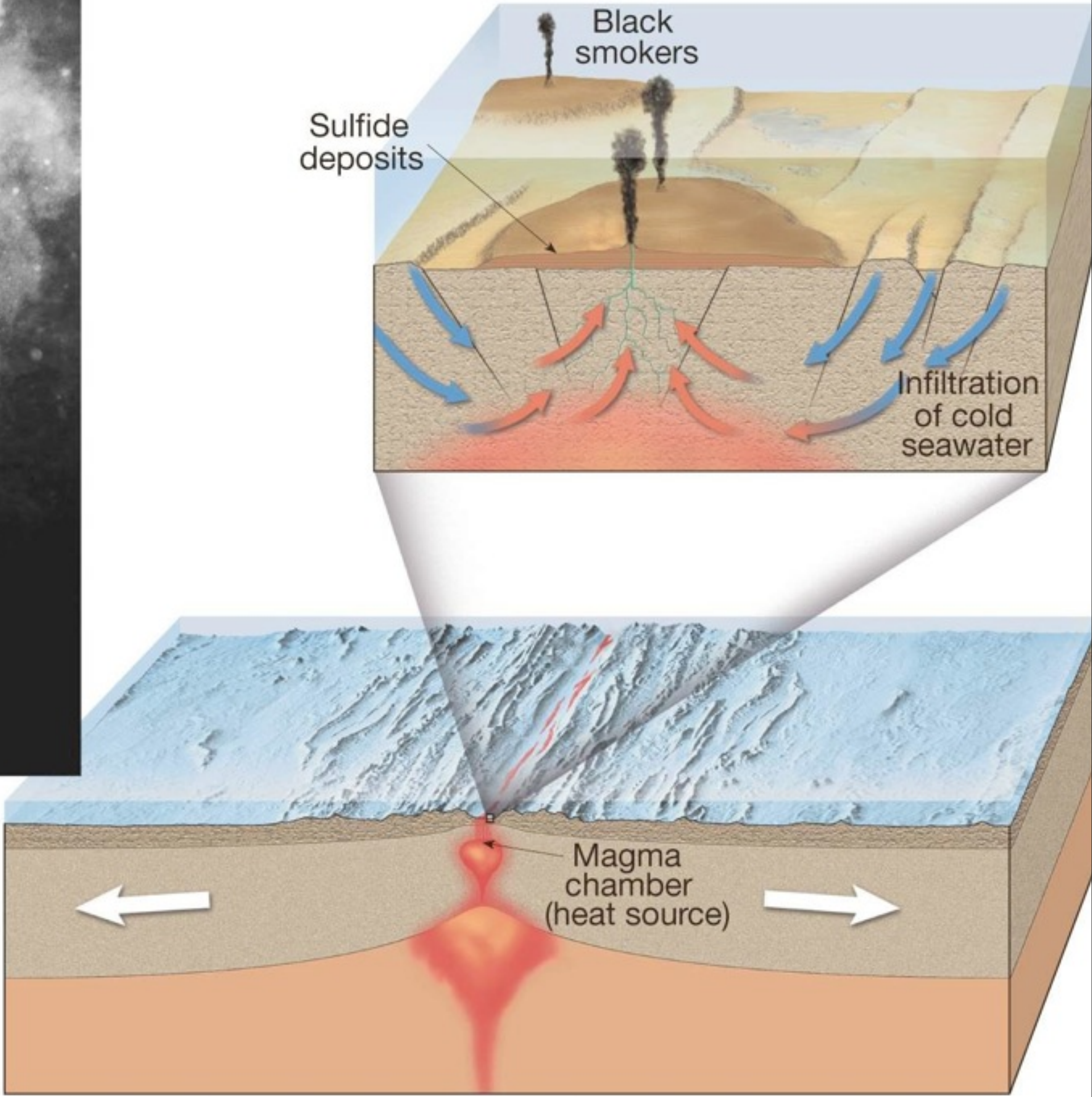
– dissolution of dispersed metals (Fe, Cu, Zn, Mn, Pb, Au) in magmatic rocks

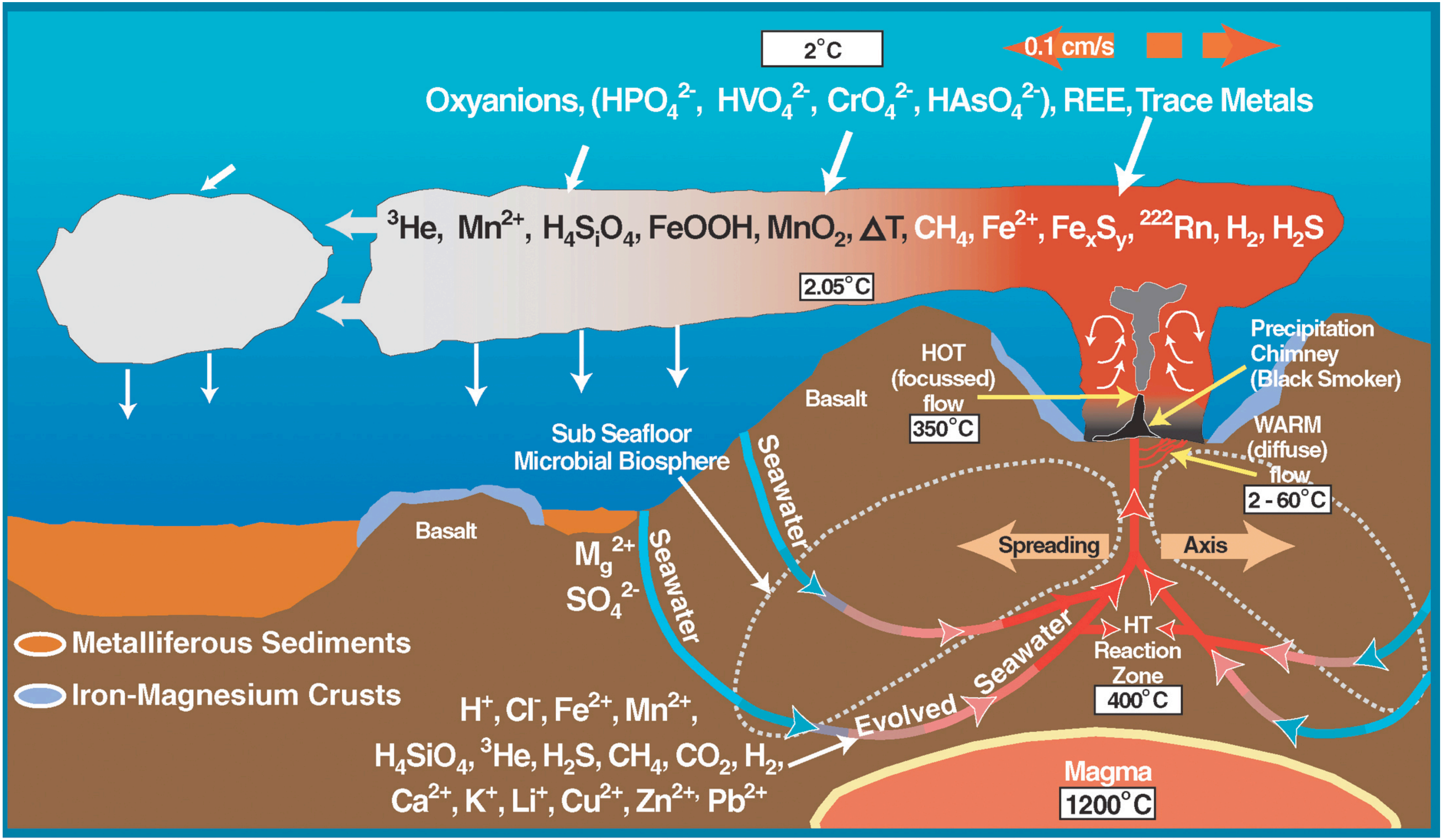
- When the metal-bearing hydrothermal fluid ascends to the seafloor it is **cooled** and **oxidized** by mixing with cold seawater:

  – Rapid cooling causes concentrated precipitation of the transported metals as **sulphide** minerals in "**black smokers**" → ore deposits (exploited where oceanic crust is exposed on land)

  – Subsequent oxidation of the hydrothermal fluid causes precipitation of **sulphates** (barite, anhydrite) in "**white smokers**", plus hematitic chert and Fe- and Mn-hydroxides




Black smokers
Sulfide deposits
Infiltration of cold seawater
Magma chamber (heat source)


2°C
0.1 cm/s
Oxyanions, (HPO_4^{2-}, HVO_4^{2-}, CrO_4^{2-}, $HAsO_4^{2-}$), REE, Trace Metals
^3He, Mn^{2+}, $H_4S_iO_4$, FeOOH, MnO_2, ΔT, CH_4, Fe^{2+}, Fe_xS_y, ^{222}Rn, H_2, H_2S
2.05°C
Precipitation Chimney (Black Smoker)
HOT (focussed) flow
350°C
Basalt
WARM (diffuse) flow
2 - 60°C
Sub Seafloor Microbial Biosphere
Seawater
Basalt
M_g^{2+}
SO_4^{2-}
Seawater
Spreading
Axis
Metalliferous Sediments
Iron-Magnesium Crusts
HT Reaction Zone
400°C
Evolved Seawater
H^+, Cl^-, Fe^{2+}, Mn^{2+},
H_4SiO_4, ^3He, H_2S, CH_4, CO_2, H_2,
Ca^{2+}, K^+, Li^+, Cu^{2+}, Zn^{2+}, Pb^{2+}
Magma
1200°C